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A RAND NOTE



# Aircraft Airframe Cost Estimating Relationships: All Mission Types

R. W. Hess, H. P. Romanoff

December 1987





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This Note is part of a series of Notes that derive a set of equations suitable for estimating the acquisition costs of various types of aircraft airframes in the absence of detailed design and manufacturing information. A single set of equations was selected as being the most representative and applicable to the widest range of estimating situations. For all mission types, the equation set uses empty weight and speed as the basic size-performance variable combination.

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# Aircraft Airframe Cost Estimating Relationships: All Mission Types

R. W. Hess, H. P. Romanoff

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The United States Air Force

A-1

RAND

# PREFACE

This Note describes the derivation of a set of equations suitable for estimating the acquisition costs of aircraft airframes in the absence of detailed design and manufacturing information. In broad form, the research updates and extends the equation set published in J. P. Large et al., *Parametric Equations for Estimating Aircraft Airframe Costs*, The RAND Corporation, R-1693-1-PA&E, February 1976, and used in the RAND aircraft cost model, DAPCA: H. E. Boren, Jr., *A Computer Model for Estimating Development and Procurement Costs of Aircraft (DAPCA-III)*, The RAND Corporation, R-1854-PR, March 1976.

The present effort was undertaken in the context of a larger overall study whose objectives included: (a) an analysis of the utility of dividing the full estimating sample into subsamples representing major differences in aircraft type (attack, fighter, and bomber/transport); and (b) an examination of the explanatory power of variables describing program structure and airframe construction techniques. Additionally, for the fighter subsample only, the study investigated the possible benefits of incorporating an objective technology measure into the equations. A detailed description of the overall study, including the research approach, evaluation criteria, and database may be found in R. W. Hess and H. P. Romanoff, *Aircraft Airframe Cost Estimating Relationships: Study Approach and Conclusions*, The RAND Corporation, R-3255-AF, December 1987.

To address the issue of sample homogeneity, each of the subsamples, as well as the full sample, had to be investigated in detail with the ultimate goal of developing representative sets of cost estimating relationships (CERs) for each. The purpose of this Note is, therefore, to document the analysis of the full estimating sample. Study results concerning the individual subsamples are available in a series of companion Notes:

*Aircraft Airframe Cost Estimating Relationships: Fighters*, N-2283/2-AF, December 1987.

*Aircraft Airframe Cost Estimating Relationships: Bombers and Transports*, N-2283/3-AF, December 1987.

*Aircraft Airframe Cost Estimating Relationships: Attack Aircraft*, N-2283/4-AF, December 1987.

This research was undertaken as part of the Project AIR FORCE study entitled "Cost Analysis Methods for Air Force Systems," which has been superseded by "Air Force Resource and Financial Management Issues for the 1980s" in the Resource Management Program.

While this report was in preparation, Lieutenant Colonel H. P. Romanoff, USAF, was on duty in the System Sciences Department of The RAND Corporation. At present, he is with the Directorate of Advanced Programs in the Office of the Assistant Secretary of the Air Force for Acquisition.

# SUMMARY

This Note presents generalized equations for estimating the development and production costs of aircraft airframes. It provides separate estimating relationships for engineering, tooling, manufacturing labor, manufacturing material, development support, flight test, and quality control as well as for total program cost. The estimating relationships, expressed in the form of exponential equations, were derived by multiple least-squares regression analysis. They were derived from a database consisting of 34 military aircraft with first flight dates ranging from 1948 to 1978. The aircraft technical data were obtained for the most part from either original engineering documents such as manufacturer's performance substantiation reports or from official Air Force and Navy documents. The cost data were obtained from the airframe manufacturers either directly from their records or indirectly through standard Department of Defense reports such as the Contractor Cost Data Reporting System.

For each airframe cost category there are generally several potentially useful estimating equations. Nevertheless, a single set of equations has been selected as being, in our judgment, the most representative and applicable to the widest range of estimating situations. The selection rationale, as well as the alternative equations and supporting data, are presented in this Note so that interested readers may make their own judgments.

The equation set selected as most representative uses empty weight and speed as the basic size/performance variable combination. It is based on a subsample of the full estimating sample consisting of 13 post-1960 aircraft. We concluded that the more limited post-1960 experience would be a better guide to the future than the cumulative experience dating back to 1948.

Our attempts to incorporate construction and program characteristics were not successful. Although variables characterizing the equipment placed within the airframe structure and a contractor's

relevant experience were frequently found to be statistically significant, they did not, as a rule, result in any substantial improvement in the quality of the equations. In most cases, the equations incorporating such variables did not produce results that we viewed as credible. Moreover, even in those few instances where the equations did produce credible results, the reduction in the standard error of estimate was never more than two or three percentage points.

The statistical quality of the set of airframe cost estimating relationships (CERs) presented here is not much different from that of the last set of RAND-developed airframe CERs (DAPCA III).[1] However, there have been some changes in the equation coefficients with the result that the current set *tends* to produce higher estimates than does the DAPCA III set.

The ultimate test will of course be the set's ability to estimate the cost of future aircraft. Unfortunately (from an estimating point of view), airframes are changing dramatically with respect to materials (e.g., more extensive use of composites), design concepts (e.g., concepts to increase fuel efficiency and to reduce radar cross-section), and manufacturing techniques (e.g., use of computers and robots). We believe that the material and design changes will act to increase unit costs but we are uncertain about the net impact of capital equipment changes. In any case, it is highly unlikely that any of the equation sets presented in this document will overestimate the costs of future aircraft.

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[1]The last set of airframe CERs is documented in J. P. Large et al., *Parametric Equations for Estimating Aircraft Airframe Costs*, R-1693-1-PA&E, February 1976, and used in the most recent version of the RAND aircraft cost model, commonly known as DAPCA: H. E. Boren, Jr., *A Computer Model for Estimating Development and Procurement Costs of Aircraft (DAPCA-III)*, R-1854-PR, March 1976.

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## FIGURES

# MNEMONICS

| | |
|---|---|
| AUW | Airframe unit weight (lb) |
| AVAUW | Ratio of avionics weight to airframe unit weight |
| BLBOX | Number of black boxes |
| CA | Cumulative average |
| CARGODV | Cargo aircraft designator (1 = no; 2 = yes) |
| CARRDV | Carrier capability designator (1 = no; 2 = yes) |
| CLIMB | Rate of climb (ft/min) |
| DS | Development support cost (thousands of 1977 dollars) |
| ENGDV | New engine designator (1 = no; 2 = yes) |
| ENGLOC | Engine location designator (1 = embedded in fuselage; 2 = in nacelles under wing) |
| $ENGR_{100}$ | Cumulative engineering hours for 100 aircraft (thousands) |
| EXPDV | Contractor experience designator (1 = yes; 2 = no) |
| EW | Empty weight (lb) |
| EWAUW | Ratio of empty weight less airframe unit weight to airframe unit weight |
| FFD | First flight date (measured in months since January 1, 1940). |
| FT | Flight test cost (thousands of 1977 dollars) |
| $LABR_{100}$ | Cumulative manufacturing labor hours for 100 aircraft (thousands) |
| $MATL_{100}$ | Cumulative manufacturing material costs for 100 aircraft (thousands of 1977 dollars) |
| PRGDV | Program type designator (1 = concurrent; 2 = prototype) |

| | |
|---|---|
| $PROG_{100}$ | Cumulative total program cost for 100 aircraft (thousands of 1977 dollars) |
| Q | Quantity |
| $QC_{100}$ | Cumulative quality control hours for 100 aircraft (thousands) |
| SP | Maximum speed (knots) |
| SPCLS | Speed class (1 = <Mach .95; 2 = Mach .95 to Mach 1.94; 3 = Mach 1.95 to Mach 2.5; 4 = >Mach 2.5) |
| TESTAC | Number of flight test aircraft |
| $TOOL_{100}$ | Cumulative tooling hours for 100 aircraft (thousands) |
| TOOLCP | Maximum tooling capability (aircraft per month) |
| USELD | Useful load fraction |
| ULTLD | Design ultimate load factor (g's) |
| WTAREA | Wetted area (sq ft) |
| WGTYPE | Wing type designator (1 = straight; 2 = swept; 3 = delta; 4 = variable sweep) |
| WGWET | Ratio of wing area to wetted area |

# EVALUATION CRITERIA NOTATION

| Notation | Explanation |
|---|---|
| EQ SIG: F-TEST | Equation as a whole is not significant at 5 percent level (based on F-statistic) |
| EXP MAG: variable mnemonic | Question exists regarding magnitude of variable exponent (reasonableness) |
| EXP SIGN: variable mnemonic | Sign of variable exponent does not agree with a priori notions |
| F | F-statistic |
| IO: aircraft identification | Based on "Cook's Distance," aircraft indicated to be influential observation |
| LDIFF: variable mnemonic | Limited differentiation in dummy variable; coefficient determined by single observation or portion of dummy variable range not included in a subsample |
| MCOL: r(variable) > .7, .8, or .9 | Indicates degree of intercorrelation of specified variable with other equation variables (only provided when threshold of .7 is exceeded) |
| N | Number of observations |
| $R^2$ | Coefficient of determination |
| RP: CUR: OVER/UNDER | Residual pattern indicates that the most recently developed aircraft in the sample are over- or underestimated |
| RP: DIST | Residual pattern indicates that the terror is not normally distributed with zero mean and constant variance |
| SEE | Standard error of estimate |
| VAR SIG: variable mnemonic | Variable is not significant at the 5 percent level (t-statistic)[1] |

[1]Variable significance is provided in parentheses beneath each variable.

# I. INTRODUCTION

Parametric models for estimating aircraft airframe acquisition costs have been used extensively in advanced planning studies and contractor proposal validation. These models are designed to be used when little is known about an aircraft design or when a readily applied validity and consistency check of detailed cost estimates[1] is necessary. They require inputs that: (a) will provide relatively accurate results; (b) are logically related to cost; and (c) can easily be projected before actual design and development. The intent is to generate estimates that include the cost of program delays, engineering changes, data requirements, and inefficiencies of all kinds that occur in a normal program.

Since 1966, RAND has developed three parametric airframe cost models.[2] These models have been characterized by: (a) easily obtainable size and performance inputs (weight and speed); (b) the estimation of costs at the total airframe level; and (c) the use of heterogeneous aircraft samples. They have normally been updated when a sufficient number of additional aircraft data points have become available to suggest possible changes in the equations. Such is the case with regards to this present effort: The A-10, F-15, F-16, F-18, F-101, and S-3 have been added to the estimating sample.[3]

In addition to expanding the database, we also examined: (a) the utility of dividing the estimating sample into subsamples representing major differences in aircraft type (attack, fighter, bomber/transport); (b) the explanatory power of variables describing program structure and

[1]Examples of this latter application include the Independent Cost Analysis (ICA) prepared as part of the Defense Systems Acquisition Review Council (DSARC) process, and government analyses of contractor cost proposals during source selections.

[2]See Refs. 1, 2, and 3.

[3]Additionally, the F-86, F-89, and F3D, which were dropped from the DAPCA-III estimating sample, were reintroduced.

airframe construction techniques; and (c) the possible benefits of incorporating an objective technology measure into the fighter sample equations. To address the issue of sample homogeneity, each subsample, as well as the full sample, had to be investigated in detail with the ultimate goal of developing representative sets[4] of cost estimating relationships (CERs) for each. The purpose of this Note is, therefore, to document the selection of a representative set of CERs for the full sample.

A detailed description of the overall study, including the research approach, evaluation criteria, and database, may be found in the companion report, R-3255-AF.

## APPROACH AND PRINCIPAL RESULTS

Our analysis produced a number of potentially useful equations for each of the airframe cost elements. In fact, this Note contains each of the 213 equations that met our initial screening criteria relative to variable significance (discussed in Sec. II). Additionally, data plots have been included for each cost element. Presenting such a large number of equations and supporting data serves two purposes. First, the information contained in the equations and plots can provide an improved understanding of the factors that influence airframe costs. Thus, the estimator will have a more complete context in which to judge the applicability of specific estimating equations. Second, we are offering the user alternatives for each cost element that may be better suited in a particular case than any single equation that we might have selected if we had chosen to document just one. This is important because, in general, the study did not produce one equation for each cost element that is clearly preferred over all others. The user should review all of the results before selecting the equations to be used in a particular situation.

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[4]A set encompasses the following cost elements: engineering, tooling, manufacturing labor, manufacturing material, development support, flight test, and quality control.

The *basic* estimating sample used in our analysis consists of 32 "new design" aircraft (seven attack aircraft, eight bombers and transports, 15 fighters, and two trainers) with first flight dates spanning the years 1948 to 1974. All cost data were obtained from an unpublished RAND study, which compiled cost and manhour data on major U.S. aircraft development and production programs from the late 1940s to 1977. All technical data were obtained either from original engineering documents or from official Air Force and Navy aircraft characteristics summaries.

As a result of our analysis of the *basic* 32 aircraft estimating sample, we identified what we felt to be the best possible equation set. Unfortunately, the engineering, manufacturing material, development support, flight test, and total program cost estimating relationships in that set tended to underestimate the costs of the most recent sample aircraft. Consequently, questions were raised concerning whether the older aircraft in the sample were representative of aircraft of the future. As a result, additional analysis of 11 post-1960 aircraft was undertaken. On the basis of this additional analysis, we concluded that the more limited post-1960 experience was a better guide to the future than the cumulative experience dating back to 1948.

After completion of the preceding analyses but before publication of this Note, however, cost data for the F-16 and F-18 became available. Consequently, a brief *follow-on analysis* was undertaken to determine whether inclusion of the F-16 and F-18 in the estimating sample would dictate modification of the previously decided upon set of CERs.[5] We concluded that from a statistical standpoint their inclusion made very little difference. However, it was felt that most users would prefer to use an equation set that was based on the most up-to-date information. Therefore, the equation set that we have chosen to recommend, and which is presented in Table 1, is based on an *expanded* post-1960 estimating sample of 13 aircraft (four attack aircraft, two transports, six

[5]The initial detailed analysis was not repeated because a great deal of effort would have been required and we simply did not feel it was warranted.

Table 1

RECOMMENDED SET OF AIRFRAME CERs

| Equation | $R^2$ | SEE | F | N |
|---|---|---|---|---|
| $ENGR_{100} = .0103\ \underset{(.000)}{EW^{.777}}\ \underset{(.000)}{SP^{.894}}$ | .72 | .55 | 13 | 13 |
| $TOOL_{100} = .0201\ \underset{(.000)}{EW^{.777}}\ \underset{(.000)}{SP^{.696}}$ | .92 | .25 | 56 | 13 |
| $LABR_{100} = .141\ \underset{(.000)}{EW^{.820}}\ \underset{(.013)}{SP^{.484}}$ | .88 | .31 | 38 | 13 |
| $MATL_{100} = .241\ \underset{(.000)}{EW^{.921}}\ \underset{(.003)}{SP^{.621}}$ | .91 | .30 | 51 | 13 |
| $DS = .0251\ \underset{(.016)}{EW^{.630}}\ \underset{(.012)}{SP^{1.30}}$ | .54 | .82 | 6 | 13 |
| $FT = .687\ \underset{(.032)}{EW^{.325}}\ \underset{(.037)}{SP^{.822}}\ \underset{(.010)}{TESTAC^{1.21}}$ | .83 | .48 | 15 | 13 |
| $QC_{100} = .076 \times LABR_{100}$ if cargo aircraft | -- | -- | -- | 2 |
| $= .133 \times LABR_{100}$ if non-cargo aircraft | -- | -- | -- | 11 |
| $PROG_{100} = 2.57\ \underset{(.000)}{EW^{.798}}\ \underset{(.003)}{SP^{.736}}$ | .85 | .36 | 29 | 13 |

NOTES: Statistics in right-hand columns are coefficient of determination, standard error of estimate (logarithm), F-statistic, and sample size. Numbers in parentheses are significance levels of individual variables.

- DS = development support cost (thousands of 1977 dollars)
- $ENGR_{100}$ = cumulative engineering hours for 100 aircraft (thousands)
- EW = empty weight (lb)
- FT = flight test cost (thousands of 1977 dollars)
- $LABR_{100}$ = cumulative manufacturing labor hours for 100 aircraft (thousands)
- $MATL_{100}$ = cumulative manufacturing material dollars for 100 aircraft (thousands of 1977 dollars)
- $QC_{100}$ = cumulative quality control hours for 100 aircraft (thousands)
- PROG = cumulative total program cost for 100 aircraft 100 (thousands of 1977 dollars)
- SP = maximum speed (kn)
- TESTAC = number of flight test aircraft
- $TOOL_{100}$ = cumulative tooling hours for 100 aircraft (thousands)

fighters, and one trainer). The ranges of the variables used in the set are as follows:

| Characteristic | Database Range |
|---|---|
| Empty weight (lb) | 9,753 - 320,085 |
| Maximum speed (kn) | 389 - 1,250+ |
| Number of flight test aircraft | 10 - 33 |

The estimating relationships in the recommended equation set vary significantly in statistical quality. Four of the CERs have standard errors of estimate of about 0.30 whereas the other three CERs have standard errors of estimate of about 0.50 or greater. None of the equations meets our standard error of estimate goal of 0.18.[6] On the other hand, the lowest standard errors of estimate in the set are associated with cost elements (tooling, labor, and material), which typically account for 66 percent of total program cost (at a quantity of 100; at a quantity of 200, these elements account for 71 percent of total program cost). Finally, we note that there is some tendency for the engineering, development support, and total program cost equations to underestimate the costs of the most recent sample aircraft.

To adjust the quantity-dependent estimating relationships to quantities other than 100,[7] the following slopes are recommended:

| | Cumulative Total Slope (%) | Cumulative Total Exponent |
|---|---|---|
| Engineering | 112 | .163 |
| Tooling | 120 | .263 |
| Manufacturing labor | 156 | .641 |
| Manufacturing material | 174 | .799 |
| Quality control | 156 | .641 |
| Total program cost | 132 | .401 |

---

[6] A logarithmic standard error of estimate of 0.18 is equivalent to -16 percent, +20 percent for the corresponding hour or dollar form of the equation.

[7] $\text{Cost}(Q_{new}) = \text{Cost}(100) * (Q_{new}/100)^{\text{exponent}}$

The manufacturing material, development support, flight test, and total program cost categories are all estimated directly in 1977 dollars. To convert the remaining cost categories, which are estimated in manhours, to 1977 dollars, the following fully-burdened hourly labor rates are suggested:

| | |
|---|---|
| Engineering | 27.50 |
| Tooling | 25.50 |
| Manufacturing labor | 23.50 |
| Quality control | 24.00 |

For estimates in 1986 dollars, the following hourly labor rates and adjustment factors are suggested:

| | |
|---|---|
| Engineering | 59.10 |
| Tooling | 60.70 |
| Manufacturing labor | 50.10 |
| Quality control | 55.40 |
| Manufacturing material (index) | 1.94 |
| Development support (index) | 1.94 |
| Flight test (index) | 1.94 |
| Total program cost (index) | 2.13 |

## NOTE ORGANIZATION

Section II provides brief descriptions of the database and statistical analysis methods. Section III provides an initial overview of the individual cost element analyses that follow. Sections IV through XI provide, by cost element, data plots, estimating relationships meeting our initial screening criterion, and the rationale for selection of "representative" equations.[8] Section XII explains the selection of the recommended equation set. Section XIII details the incorporation of the F-16 and F-18 data. Finally, Sec. XIV summarizes the main findings of the analysis.

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[8]As stated above, the detailed analysis was not repeated when the F-16/F-18 data were obtained. Therefore, Secs. II-XII are based on the 32 aircraft estimating sample that does *not* include the two most recent fighters.

Three appendixes contain miscellaneous supporting information. Appendix A describes a way to address mission designation that does not require separate samples. Appendix B contains two correlation matrices: one of potential explanatory variables with the dependent cost variables and one of potential explanatory variables with other potential explanatory variables.

# II. DATABASE AND ANALYTICAL APPROACH

As stated above, a detailed description of the research approach, evaluation criteria, and database for this study may be found in R-3255-AF. However, to give this Note a degree of self-sufficiency, a synopsis of the database and analytical approach is presented before the reporting of results.

## ESTIMATING SAMPLE

The "basic" all-mission type estimating sample consists of the following 32 "new-design" aircraft.[1]

| Model | First Flight Date | Model | First Flight Date[2] |
|---|---|---|---|
| A-3 | 1953 | F4D | 1954 |
| A-4 | 1954 | F-4 | 1961 |
| A-5 | 1958 | F-14 | 1970 |
| A-6 | 1960 | F-15 | 1972 |
| A-7 | 1965 | F-86 | 1948 |
| A-10 | 1974 | F-89 | 1950 |
| B-52 | 1954 | F-100 | 1953 |
| B-58 | 1957 | F-101 | 1954 |
| B/RB-66 | 1954 | F-102 | 1955 |
| C-5 | 1968 | F-104 | 1956 |
| C-130 | 1955 | F-105 | 1956 |
| C-133 | 1956 | F-106 | 1956 |
| KC-135 | 1957 | F-111 | 1967 |
| C-141 | 1963 | S-3 | 1972 |
| F3D | 1950 | T-38 | 1959 |
| F3H | 1955 | T-39 | 1960 |

[1]The classification of an iarcraft as new or derivative is not an entirely objective procedure. For example, although the F-102A program laid the groundwork for the F-106A, the F-106A is classified as a new design in the database because, in contrast to the F-102A, it had a new engine, relocated air intakes, variable-geometry air inlets, a modified vertical stabilizer, and markedly better performance.

[2]The first flight dates presented in this report relfect the first flight date of the version that was most representative of the aircrft that was to become operational. These dates thus reflect the first flight date of the developmental aircraft, not earlier experimental or prototype aircrft. Thus, although the F-4A aircraft first flew in May 1958, the first flight date of the F-4B aircraft is presented.

## DEPENDENT VARIABLES

Costs have been dealt with at both the total program level[3] and at the major cost element level (engineering, tooling, manufacturing labor, manufacturing material, development support, flight test, and quality control).[4] The relative importance of the various cost elements (in terms of percent of total program cost) is shown below for four alternative production quantities:

| Cost Element | Quantity 25 | Quantity 50 | Quantity 100 | Quantity 200 |
|---|---|---|---|---|
| Engineering | 24 | 22 | 18 | 15 |
| Tooling | 19 | 18 | 16 | 13 |
| Manufacturing labor | 25 | 30 | 35 | 40 |
| Manufacturing material | 10 | 12 | 16 | 20 |
| Development support | 9 | 7 | 5 | 4 |
| Flight test | 10 | 8 | 6 | 4 |
| Quality control | 3 | 3 | 4 | 4 |
| | 100 | 100 | 100 | 100 |

Clearly, other things being equal, one would want the estimating relationships derived for the two manufacturing categories to be the most accurate because of the relatively large contribution of these elements to the program cost.

Engineering, tooling, manufacturing labor, and quality control are estimated in terms of manhours rather than dollars for two reasons: (a) it avoids the need to make adjustments for annual price changes, and (b) it permits comparison of real differences in labor requirements.[5]

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[3]Total program costs are "normalized" values and not the actual reported dollar amounts. They are normalized in the sense that the dollar amounts for engineering, tooling, manufacturing labor, and quality control have been determined by applying fully burdened, industry-average labor rates to the hours reported for each category.

[4]Cost element definitions are provided in Appendix A of R-3255-AF.

[5]The major limitation of the manhour approach is that it does not account for differences in overhead rates. Consequently, differences in such things as capital/labor ratios cannot be addressed.

Manufacturing material, development support, and flight test do not lend themselves to this approach and were therefore estimated in terms of dollars (in this case, constant 1977 dollars).

## POTENTIAL EXPLANATORY VARIABLES

To have been included among the characteristics that were considered for inclusion in the CERs, the following requirements must have been fulfilled:

1. The variable had to be logically related to cost: that is, a rationale had to be constructed explaining why cost should be influenced by the variable;

2. The variable had to be one that was "readily available" in the early stages of aircraft conceptualization; and

3. The variable had to have an *available* historical record.

During the formulation stage of this study, 20 aircraft characteristics were identified as potential explanatory variables for the total sample CERs. Values for these characteristics, which are grouped into four general categories (size, performance, construction, and program) are provided in Table 2. Using information in this table, the following observations can be made:

1. Minimum and maximum values for airframe unit weight, empty weight, wetted area, speed, and climb rate each span a range of over an order of magnitude.

2. Several of the continuous variables have maximum values that fall substantially beyond two standard deviations: airframe unit weight, empty weight, wetted area, speed, climb rate, number of black boxes, number of test aircraft, and maximum tooling capability.

3. Using any of the three size measures, the C-5 is approximately twice as large as the next largest aircraft in the sample.

4. The sample does not include any aircraft that are both relatively large and relatively fast (such as the B-1 would have been--airframe unit weight of approximately 150,000 lb and speed of Mach 2). This point is illustrated in Fig. 1.

Table 2

AIRCRAFT CHARACTERISTIC VALUES

| | Size | | | Technical/Performance | | | | Construction | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Aircraft | Airframe Unit Weight | Empty Weight | Wetted Area | Maximum Speed | Speed Class | Climb Rate | Useful Load Fraction | Design Ultimate Load Factor | Carrier Capability Designator | Engine Location Designator | Wing Type | Ratio of Wing Area to Wetted Area |
| A-3 | 23,931 | 35,999 | 3,899 | 546 | 1 | 5,050 | .485 | 5.00 | 2 | 2 | 2 | .200 |
| A-4 | 5,072 | 9,146 | 1,144 | 565 | 1 | 8,400 | .594 | 10.50 | 2 | 1 | 2 | .227 |
| A-5 | 23,499 | 32,714 | 2,950 | 1147 | 3 | 27,900 | .439 | 11.00 | 2 | 1 | 2 | .237 |
| A-6 | 17,150 | 25,298 | 2,100 | 561 | 1 | 10,000 | .583 | 9.75 | 2 | 1 | 2 | .251 |
| A-7 | 11,621 | 15,497 | 1,690 | 595 | 1 | 8,580 | .578 | 10.50 | 2 | 1 | 2 | .222 |
| A-10 | 14,842 | 19,856 | 2,463 | 389 | 1 | 5,100 | .559 | 4.93 | 1 | 2 | 1 | .205 |
| B-52 | 112,672 | 117,816 | 16,650 | 551 | 1 | 5,120 | .605 | 3.00 | 1 | 2 | 2 | .240 |
| B-58 | 32,686 | 55,560 | 5,450 | 1147 | 3 | 17,830 | .659 | 3.00 | 1 | 2 | 3 | .283 |
| B/RB-66 | 30,496 | 42,549 | 4,372 | 548 | 1 | 5,000 | .487 | 4.80 | 1 | 2 | 2 | .178 |
| C-5 | 279,145 | 320,085 | 30,800 | 495 | 1 | 5,160 | .555 | 3.75 | 1 | 2 | 2 | .201 |
| C-130 | 43,446 | 58,107 | 7,590 | 326 | 1 | 3,900 | .532 | 3.75 | 1 | 2 | 1 | .230 |
| C-133 | 96,312 | 114,690 | 13,150 | 304 | 1 | 3,400 | .617 | 3.75 | 1 | 2 | 1 | .203 |
| KC-135 | 70,253 | 97,030 | 10,770 | 527 | 1 | 5,900 | .677 | 3.75 | 1 | 2 | 2 | .226 |
| C-141 | 104,322 | 136,900 | 14,100 | 491 | 1 | 7,270 | .579 | 3.75 | 1 | 2 | 2 | .229 |
| F3D | 10,136 | 14,860 | 1,843 | 470 | 1 | 4,100 | .484 | 9.00 | 2 | 1 | 1 | .218 |
| F3H | 13,898 | 21,270 | 1,908 | 622 | 1 | 13,000 | .455 | 11.25 | 2 | 1 | 2 | .272 |
| F4D | 8,737 | 16,050 | 1,500 | 628 | 1 | 20,200 | .427 | 9.50 | 2 | 1 | 3 | .371 |
| F-4 | 17,220 | 27,530 | 2,150 | 1222 | 3 | 40,600 | .508 | 12.75 | 2 | 1 | 2 | .247 |
| F-14 | 26,500 | 36,825 | 3,155 | * | * | * | * | * | 2 | 1 | 4 | .179 |
| F-15 | 17,550 | 26,795 | 2,646 | * | * | * | .499 | 11.00 | 1 | 1 | 2 | .230 |
| F-86 | 6,788 | 10,040 | 1,070 | 590 | 1 | 7,650 | .416 | 11.00 | 1 | 1 | 2 | .269 |
| F-89 | 18,119 | 23,870 | | 546 | 1 | 11,800 | .347 | 8.50 | 1 | 1 | 1 | |
| F-100 | 12,118 | 18,260 | 1,509 | 752 | 2 | 25,700 | .371 | 11.00 | 1 | 1 | 2 | .255 |
| F-101 | 13,423 | 24,720 | 2,060 | 872 | 2 | 29,600 | .493 | 11.00 | 1 | 1 | 2 | .179 |
| F-102 | 12,304 | 19,460 | 2,170 | 680 | 2 | 18,700 | .374 | 10.50 | 1 | 1 | 3 | .305 |
| F-104 | 7,963 | 11,570 | 1,078 | 1150 | 3 | 51,500 | .508 | 11.00 | 1 | 1 | 2 | .182 |
| F-105 | 19,301 | 24,500 | 1,998 | 1112 | 3 | 38,300 | .538 | 13.00 | 1 | 1 | 2 | .193 |
| F-106 | 14,620 | 23,180 | 2,230 | 1153 | 3 | 34,500 | .363 | 10.50 | 1 | 1 | 3 | .312 |
| F-111 | 33,150 | 46,170 | 2,580 | 1262 | 3 | 12,600 | .533 | 11.00 | 1 | 1 | 4 | .203 |
| S-3 | 18,536 | 26,581 | 2,607 | 429 | 1 | 5,000 | .494 | 5.25 | 2 | 2 | 2 | .230 |
| T-38 | 5,376 | 7,410 | | 699 | 2 | 28,500 | .387 | 11.00 | 1 | 1 | 2 | |
| T-39 | 7,027 | 9,753 | | 468 | 1 | 4,2[illegible]0 | .477 | 11.00 | 1 | 2 | 2 | |
| Mean | 35,257 | 47,815 | 5,091 | 734 | -- | 17,942 | .503 | 8.41 | -- | -- | -- | .234 |
| Standard Deviation | 52,769 | 63,306 | 6,475 | 320 | -- | 16,129 | .086 | 3.34 | -- | -- | -- | .044 |
| Range | 5,072-279,145 | 7,410-320,085 | 1,070-30,800 | 304-1250+ | -- | 3,400-50,000+ | .347-.677 | 3.00-13.00 | -- | -- | -- | .178-.371 |

* = Classified

Blank = Not available

Table 2 (continued)

AIRCRAFT CHARACTERISTIC VALUES

| | Construction (continued) | | | Program | | | | |
|---|---|---|---|---|---|---|---|---|
| Aircraft | Ratio of (EW-AUW) to AUW | Ratio of Avionics Wt to AUW | Number of Black Boxes | Number of Test Aircraft | Maximum Tooling Capability | New Engine Designator | Contractor Experience Designator | Program Type Designator |
| A-3 | .50 | .085 | 8 | 5 | 8 | 1 | 2 | 2 |
| A-4 | .80 | .084 | 6 | 9 | 40 | 1 | 1 | 2 |
| A-5 | .39 | .110 | 13 | 11 | 6 | 1 | 2 | 1 |
| A-6 | .48 | .170 | 23 | 8 | 8 | 2 | 2 | 1 |
| A-7 | .33 | .059 | 19 | 7 | 24 | 1 | 1 | 1 |
| A-10 | .34 | .041 | 14 | 8 | 15 | 1 | 2 | 2 |
| B-52 | .58 | .070 | 24 | 13 | 10 | 2 | 1 | 2 |
| B-58 | .70 | | 26 | 30 | 8 | 2 | 2 | 1 |
| B/RB-66 | .40 | .092 | | 14 | 10 | 2 | 1 | 1 |
| C-5 | .15 | .017 | 27 | 10 | 2 | 2 | 1 | 1 |
| C-130 | .34 | .035 | 17 | 9 | 18 | 2 | 2 | 2 |
| C-133 | .19 | .021 | 16 | 10 | 2 | 2 | 1 | 1 |
| KC-135 | .38 | | 16 | 8 | 15 | 1 | 1 | 2 |
| C-141 | .31 | .023 | 26 | 5 | 9 | 1 | 1 | 1 |
| F3D | .47 | .145 | 9 | 13 | 20 | 1 | 2 | 2 |
| F3H | .53 | .060 | 6 | 18 | 13 | 2 | 1 | 2 |
| F4D | .84 | .215 | 9 | 13 | 20 | 2 | 1 | 2 |
| F-4 | .60 | .101 | 14 | 7 | 15 | 1 | 1 | 1 |
| F-14 | .39 | .112 | 21 | 12 | 8 | 1 | 1 | 1 |
| F-15 | .53 | .090 | 24 | 20 | 12 | 2 | 1 | 1 |
| F-86 | .48 | .106 | 4 | 12 | 30 | 2 | 1 | 2 |
| F-89 | .32 | | 9 | 6 | 25 | 1 | 2 | 2 |
| F-100 | .51 | .016 | 5 | 13 | 50 | 1 | 1 | 2 |
| F-101 | .84 | .075 | 9 | 17 | 20 | 1 | 1 | 1 |
| F-102 | .58 | .164 | 9 | 31 | 45 | 1 | 2 | 1 |
| F-104 | .45 | .076 | 6 | 19 | 20 | 2 | 1 | 2 |
| F-105 | .27 | .074 | 11 | 15 | 17 | 2 | 1 | 1 |
| F-106 | .59 | .190 | 11 | 26 | 29 | 1 | 1 | 1 |
| F-111 | .39 | .081 | 18 | 18 | 21 | 2 | 2 | 1 |
| S-3 | .44 | .220 | 33 | 8 | 5 | 2 | 2 | 1 |
| T-38 | .38 | | 7 | 14 | 24 | 1 | 2 | 2 |
| T-39 | .39 | | 10 | 4 | 5 | 2 | 1 | 2 |
| Mean | .47 | .094 | 14 | 13 | 17 | -- | -- | -- |
| Standard Deviation | .17 | .058 | 8 | 7 | 12 | -- | -- | -- |
| Range | .15-.84 | .016-.220 | 4-33 | 4-31 | 2-50 | -- | -- | -- |

* = Classified
Blank = Not available

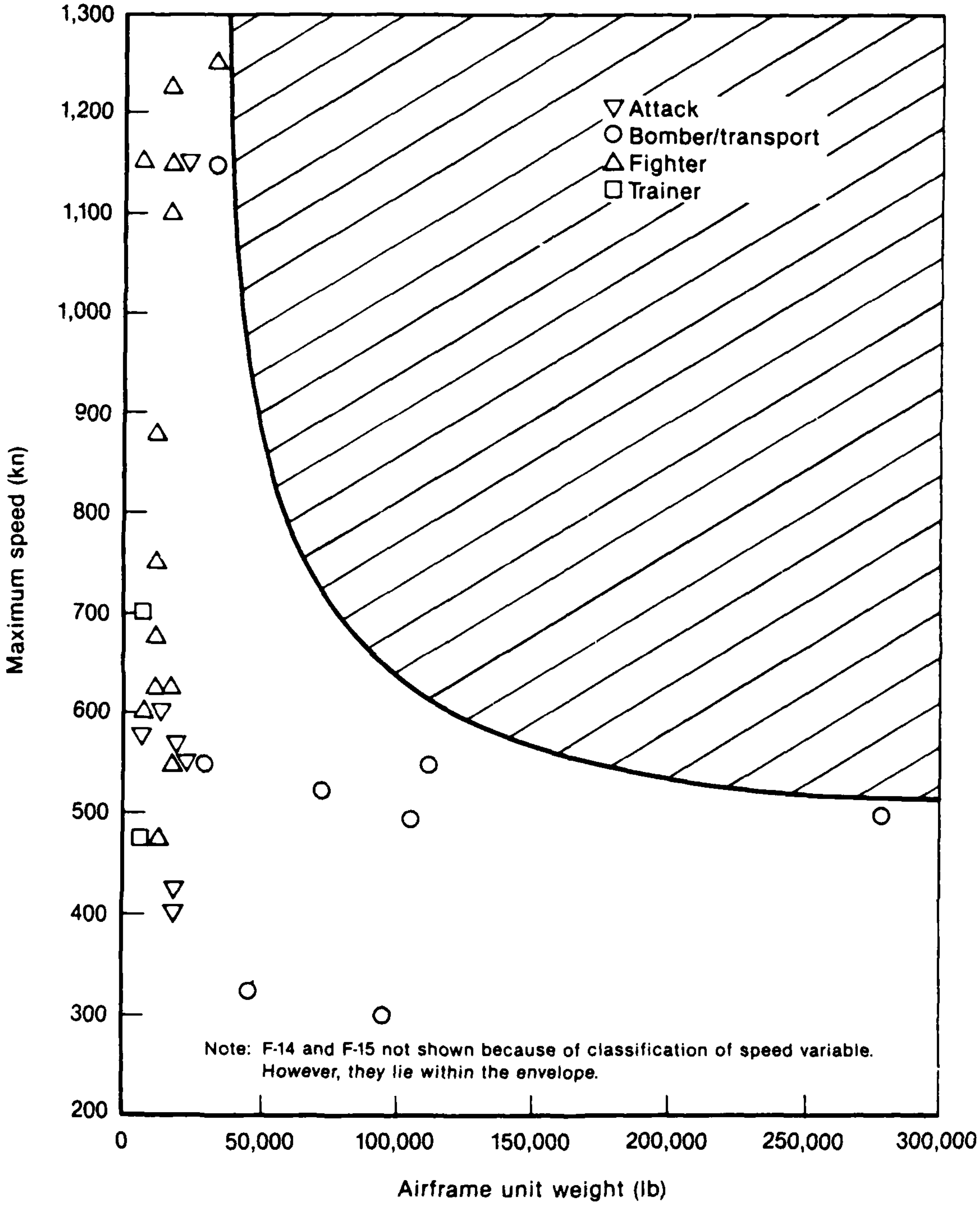



Fig. 1—Speed versus weight

A summary breakdown (Table 3) indicates how the characteristics vary with mission type. As one would expect, the fighter and attack aircraft are roughly comparable in size with the bombers and transports much larger. In terms of combat engagement characteristics (speed, climb rate, and design ultimate load factor), the ordering (from low to high) is bomber/transport, attack, and fighter, whereas for payload capability (useful load fraction) the order is reversed. In terms of the two packaging ratios (ratio of EW-AUW to AUW and ratio of avionics weight to AUW), the attack and fighter aircraft are essentially equivalent and the bomber/transport aircraft are significantly lower. On the other hand, the bomber/transports have, on average, substantially more black boxes than do either the attack or fighter aircraft. Finally, we note that, on average, planned production rates for attack and fighter aircraft are roughly twice those of bomber/transport aircraft.

There are, of course, differences between the aircraft that are not accounted for in Tables 2 or 3. Some of the differences relate to the way an aircraft is constructed (materials, manufacturing technology), others to the way the program is managed. In any case, it is difficult to find an aircraft without at least one unique aspect. Therefore, the following list is intended only to be indicative of the types of differences that are difficult to account for in a generalized parametric model.

1. The C-130 and C-133 are prop aircraft whereas all other sample aircraft use turbojet or turbofan engines.

2. The KC-135 was designed and produced more or less concurrently with the commercial 707 model.

3. The B/RB-66 was produced concurrently with the A-3, the aircraft from which it evolved.

4. The F-102 did not meet its speed performance specifications until after a major redesign.

Table 3

SUMMARY OF AIRCRAFT CHARACTERISTIC VALUES BY MISSION TYPE

| Explanatory Variable | All Mission Types (32 observations) | | Attack Aircraft (7 observations) | | Bombers & Transports (8 observations) | | Fighters (15 observations) | |
|---|---|---|---|---|---|---|---|---|
| | Mean | Range | Mean | Range | Mean | Range | Mean | Range |
| SIZE | | | | | | | | |
| Airframe unit weight (AUW) | 35257 | 5072-279145 | 16379 | 5072-23931 | 96167 | 30496-279145 | 15455 | 6788-33150 |
| Empty weight (EW) | 47815 | 7410-320085 | 23584 | 9146-35999 | 125342 | 42549-320085 | 23007 | 10040-46170 |
| Wetted area | 5091 | 1070-30800 | 2408 | 1144-3899 | 12860 | 4372-30800 | 1993 | 1070-3155 |
| PERFORMANCE | | | | | | | | |
| Maximum speed | 734 | 304-1250+ | 605 | 389-1147 | 549 | 304-1147 | 913 | 470-1250+ |
| Climb rate | 17942 | 3400-50000+ | 10004 | 5000-27900 | 6698 | 3400-17830 | 27850 | 4100-50000+ |
| Useful load fraction | .503 | .347-.677 | .533 | .439-.594 | .589 | .487-.677 | .453 | .347-.538 |
| CONSTRUCTION | | | | | | | | |
| Design ultimate load factor | 8.41 | 3.00-13.00 | 8.13 | 4.93-11.00 | 3.69 | 3.00-4.80 | 10.72 | 8.50-13.00 |
| Ratio of (EW-AUW) to AUW | .47 | .15-.84 | .47 | .34-.80 | .38 | .15-.70 | .52 | .27-.84 |
| Ratio of avionics weight to AUW | .094 | .016-.220 | .110 | .041-.220 | .043 | .017-.092 | .108 | .016-.215 |
| Number of black boxes | 15 | 4-33 | 17 | 6-33 | 22 | 16-27 | 11 | 4-24 |
| PROGRAM | | | | | | | | |
| Number of test aircraft | 13 | 4-31 | 8 | 5-11 | 12 | 5-30 | 16 | 6-31 |
| Maximum tooling capability | 17 | 2-50 | 15 | 5-40 | 9 | 2-18 | 22 | 8-50 |

5. The F-106 and A-7 were outgrowths of the F-102 and F-8 programs, respectively.

6. The F-111 was the first aircraft for which common Air Force/Navy usage was made a requirement at inception.

7. The B-58's use of honeycombed skin panels represented a major state-of-the-art advance.

8. The C-5 program used the acquisition concepts of total package procurement and concurrent development and production.

9. The A-10 program used the acquisition concepts of competitive prototyping and design-to-cost.

A priori notions regarding the effect of an increase in the value of an explanatory variable on each of the cost elements is indicated in Table 4. A plus indicates a positive effect, a minus a negative effect. An effect thought to be negligible is indicated by a blank, and an uncertain effect is indicated by a question mark.

## APPROACH

Potential explanatory variables have been divided into four general categories--size, performance, construction, and program (see Table 4). Ideally, an airframe cost estimating relationship would incorporate at least one variable from each category. But from a practical standpoint, concern about collinearity among the explanatory variables in two of the categories (size and performance) led to a limit of one on the number of explanatory variables that could be incorporated into an estimating relationship from any single category. Thus, there could be as many as four variables per equation but no more than four.

With respect to the specific combinations of variable categories examined, it is our understanding that all airframe manufacturers use some measure of size (usually weight) as their basic scaling dimension in developing cost estimates (although other factors frequently do enter in). Consequently, it seemed reasonable for a similar assumption to be made on our part--a size variable must appear in all equations (except for flight test in which case the number of test aircraft was the mandatory variable). Therefore, the specific variable combinations that were considered for the full estimating sample are as follows:

Table 4

A PRIORI NOTIONS REGARDING EFFECT OF INCREASE IN EXPLANATORY VARIABLE ON COST ELEMENT

| Explanatory Variable | Engr. | Tooling | Mfg. Labor | Mfg. Material | Dev. Support | Flight Test | Quality Control | Total Program |
|---|---|---|---|---|---|---|---|---|
| SIZE | | | | | | | | |
| Airframe unit weight (AUW) | + | + | + | + | + | + | + | + |
| Empty weight (EW) | + | + | + | + | + | + | + | + |
| Wetted area | + | + | + | + | + | + | + | + |
| TECHNICAL/PERFORMANCE | | | | | | | | |
| Maximum speed | + | + | + | + | + | + | + | + |
| Speed class (a) | + | + | + | + | + | + | + | + |
| Climb rate | + | + | + | + | + | + | + | + |
| Useful load fraction | + | + | + | + | | | | + |
| CONSTRUCTION | | | | | | | | |
| Design ultimate load factor | + | | + | + | + | | | + |
| Carrier capability designator (b) | + | | + | + | + | + | | + |
| Engine location designator (c) | - | ? | - | + | | | | ? |
| Wing type (d) | + | + | + | | + | + | | + |
| Ratio of wing area to wetted area | | - | - | | | | | - |
| Ratio of (EW-AUW) to AUW | + | | + | + | + | + | + | + |
| Ratio of avionics weight to AUW | + | | + | + | + | + | + | + |
| Number of black boxes | + | | + | + | + | + | + | + |
| PROGRAM | | | | | | | | |
| Number of test aircraft | | | | | | + | | |
| Maximum tooling capability | | + | - | | | | | ? |
| New engine designator (b) | + | | | | | + | | + |
| Contractor experience designator (e) | + | + | + | + | + | + | + | + |
| Program type designator (f) | ? (g) | ? (g) | | | ? (g) | ? (g) | | ? (g) |

(a)Speed class: 1 = less than Mach .95; 2 = Mach .95 to Mach 1.94; 3 = Mach 1.95 to Mach 2.5; 4 = greater than Mach 2.5.
(b)No = 1; Yes = 2.
(c)Engine location: embedded in fuselage = 1; in nacelles under wing = 2.
(d)Wing type: 1 = straight; 2 = swept; 3 = delta; 4 = variable sweep.
(e)Yes = 1; No = 2.
(f)Program type: concurrent = 1; prototype = 2.
(g)Not known whether total cost (prototype effort plus full-scale development) for prototype program is greater or less than for concurrent program.

Size
Size/performance
Size/performance/construction
Size/performance/program
Size/performance/construction/program

An additional complication arose from the fact that we were not developing a single CER but rather a *set* of CERs. Normally, the development of a representative set of CERs would require the selection of the "best" equation for each cost element. However, past experience indicates that in so doing the resulting equation set would contain different size and performance variables (e.g., airframe unit weight/speed and empty weight/climb rate). Such a result would put the analyst in the unenviable position of trying to explain why a given size/performance variable combination predicts cost more accurately for one cost element whereas another size/performance variable combination predicts cost more accurately for another cost element. Furthermore, because of variable interaction (e.g., such as between speed and rate of climb), the user's input task would become more difficult. On the other hand, there is nothing to say that such mixing of the size and performance variables could not in fact be the preferred solution. Consequently, two types of equation sets have been developed: one that maintains the integrity of the set size and performance variables and one that uses the "best" equation for each cost element regardless of the size or performance variables.

The first step in developing a representative set of CERs was to identify all potentially useful estimating relationships for each cost element resulting from the variable combinations listed above. For this first step, "potentially useful" included only those estimating relationships in which all equation variables were significant at the 5 percent level. For the one- and two-variable combinations, all possible equations were examined. An initial inspection was next undertaken to identify the "most promising" size/performance combinations. Then, for the three-variable combinations, each construction and program variable was examined in conjunction with the "most promising" size/performance

variable combinations. For the four variable combinations, the regressions that were run were based on intuition developed in the preceding analyses of the two- and three-variable combinations.

Each equation satisfying the initial screening criterion (5 percent variable significance) was then scrutinized in accordance with a set of evaluation criteria dealing with statistical quality and reasonableness of results (these are described in a subsequent subsection).

The next step was to develop the two types of alternative equation sets discussed previously. For the first type, this consisted of selecting the "best" estimating relationship for each of the "most promising" size/performance combinations for each cost element. For the second type, it consisted of selecting the single "best" estimating relationship for each cost element. Generally speaking, we tried to select estimating relationships that satisfied the following conditions:

- Each variable was significant at the 5 percent level.
- Variables taken collectively were significant at the 5 percent level.
- They produced credible results.
- They were free of unusual residual patterns.

Once these conditions were satisfied, the objective was minimization of the standard error of estimate. Traditionally, cost analysts have *tried* to achieve a standard error of estimate of $\pm 20$ percent or better. For logarithmic models, this is approximately equivalent to 0.18 (-16 percent, +20 percent).

The final step was the selection of a "most" representative set. This final selection was done primarily on the basis of a comparison of the individual equation standard errors of estimate and by how well (in terms of relative deviation) the sets as a whole estimated the costs of a subsample of four recent aircraft.

Multiple regression analysis was used to examine the relationship between cost and the explanatory variables. Because of time restrictions, only one equation form was investigated--logarithmic-linear. The logarithmic equation form was selected over the linear and exponential equation forms by a process of elimination. The linear model was rejected because its main analytic property--constant returns to scale--did not correspond to real world expectations. Of the two remaining equation forms, the logarithmic model seemed most appropriate for the cost estimation process, since it minimized relative errors rather than actual errors as in the exponential model.

Cost element categories that are a function of quantity were examined at a quantity of 100. Developing the estimating relationships at a given quantity rather than using quantity as an independent variable in the regression analysis avoids the problem of unequal representation of aircraft (caused by unequal numbers of lots).

## EVALUATION CRITERIA

The estimating relationships obtained in this analysis were evaluated on the basis of their statistical quality, intuitive reasonableness, and predictive properties.

### Statistical Quality

**Variable Significance**. Variable significance was used as an initial screening device to reduce the number of estimating relationships requiring closer scrutiny. Normally, only those equations for which all variables were significant at the 5 percent level (one-sided t-test) are reported in this Note. Occasionally, however, this criterion was relaxed to allow a useful comparison or so that the requirement concerning the integrity of the set size and performance variables could be examined. When an equation is reported for which not all equation variables are significant at the 5 percent level, it is denoted as follows:

VAR SIG: variable mnemonic

**Coefficient of Determination**. The coefficient of determination ($R^2$) was used to indicate the percentage of variation explained by the regression equation.

**Standard Error of Estimate**. The standard error of estimate (SEE) was used to indicate the degree of variation in the data about the regression equation. It is given in logarithmic form but may be converted into a percentage of the corresponding hour or dollar value by performing the following calculations:

(a) $e^{+SEE}-1$

(b) $e^{-SEE}-1$

For example, a standard error of 0.18 yields standard error percentages of +20 and -16.

**F-Statistic**. The F-statistic was used to determine collectively whether the explanatory variables being evaluated affect cost. Those equations for which the probability of the null hypothesis pertaining was greater than 0.05 have been identified as follows:

EQ SIG: F-TEST

Generally speaking, equations so identified were not considered for inclusion in a representative equation set.

**Multicollinearity**. Estimating relationships containing variable combinations with correlations greater than .70 are identified according to the degree of intercorrelation:

MCOL: r(variable mnemonic) > .7, .8, or .9

where the variable identified in parentheses is the equation variable showing the greatest collinearity. Generally speaking, estimating relationships with intercorrelations greater than .8 were avoided when selecting a representative equation set.

**Residual Plots.** Plots of equation residuals were given cursory examinations for unusual patterns. In particular, plots of residuals versus predictions (log/log) were checked to make sure that the error term was normally distributed with zero mean and constant variance. Additionally, plots of residuals versus time (log/linear) were examined to see whether or not the most recent airframe programs were over- or underestimated. The existence of such patterns resulted in one of the following designations:

RP: DIST (errors not normally distributed)
RP: CUR:OVER or UNDER (most recent aircraft over- or underestimated)

Generally speaking, we *tried* to avoid the use of estimating relationships with patterns in the representative equation sets.

**Influential Observations.** "Cook's Distance" was used to identify influential observations in the least squares estimates. For this analysis, an influential observation was defined as one which, if deleted from the regression, would move the least squares estimate past the edge of the 10 percent confidence region for the equation coefficients. Such observations are identified as follows:

IO: aircraft identification

When an observation was consistently identified as influential, it was reassessed in terms of its relevance to the sample in question. If a reasonable and uniform justification for its exclusion could be developed, then the observation was deleted from the sample and the

regressions rerun (in actuality, this occurred only once--when the B-58 was deleted from the bomber/transport sample). Otherwise, the influential observation was simply flagged to alert the potential user to the fact that its deletion from the regression sample would result in a significant change in the equation coefficients.

### Reasonableness

The development of airframe cost estimating relationships requires variable coefficients that both provide credible results and conform whenever possible to the normal estimating procedures employed by the airframe industry. Such credibility and conformity are reflected in both the signs of the variable coefficients as well as their magnitudes.

**Exponent Sign.** Estimating relationships for which the sign of the variable coefficient was not consistent with a priori notions (see Table 4) are identified in the following manner:

EXP SIGN: variable mnemonic

Estimating relationships containing such inconsistencies were not considered for inclusion in the representative equation sets.

**Exponent Magnitude.** Close attention was also paid to the magnitude of variable coefficients. This applied to exponents that were felt to be too small as well as to those that were felt to be too large. Estimating relationships containing such variable coefficients are identified as follows:

EXP MAG: variable mnemonic

Although determinations of this kind are largely subjective, there was one application that was relatively objective. Traditionally, size variables have always provided returns to scale in the production-oriented cost elements (tooling, labor, material, and total program cost). That is, increases in airframe size are accompanied by less than proportionate increases in cost. If the opposite phenomenon is

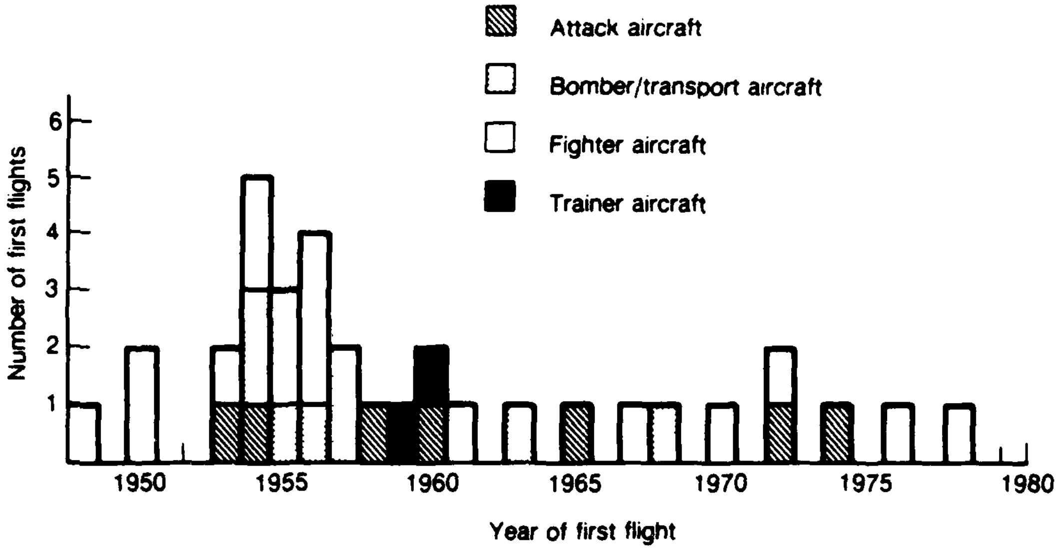
observed, then it is generally believed to be the result of not adequately controlling for differences in construction, materials, complexity, or other miscellaneous production factors. Consequently, equations possessing a size-variable coefficient greater than one were always flagged.

When selecting a representative equation set, we generally tried to avoid estimating relationships containing variables with exponents that we felt were either too large or too small (that is, exponents that placed either too much or too little emphasis on the parameters in question). More restrictively, for the production-oriented cost elements, no estimating relationship possessing a size-variable exponent greater than one was considered for a representative equation set.

### Predictive Properties

Confidence in the ability of an equation to accurately estimate the acquisition cost of a future aircraft is in large part dependent on how well the acquisition costs of the most recently produced aircraft are estimated. Normally, statistical quality and predictive capability would be viewed as one and the same. Unfortunately, when dealing with airframe costs this is not always the case because our knowledge of what drives airframe costs is limited and because the sample is relatively small in size and not evenly distributed with respect to first flight date (see Fig. 2). Consequently, the estimating relationships were also evaluated on the basis of how well costs for a subset of the most recent aircraft in the database are estimated.

An indication of an equation's predictive capability would usually be obtained by excluding a few of the most recent aircraft from the regression and then seeing how well (in terms of the relative deviation) the resultant equation estimates the excluded aircraft. However, in this case, the small sample size precluded this option. Consequently, the measure of predictive capability used in this analysis was the average of the absolute relative deviations for the A-10, C-141, F-14,




Note: Only aircraft in the RAND airframe cost data base are reflected in this figure. Consequently, the figure specifically excludes the first flights of modification aircraft, aircraft that never entered production (e.g., the F-107), and recent aircraft for which a production quantity of 100 has not yet been reached (e.g., the B-1B).

Fig. 2—Number of first flight events as a function of the year of first flight

and F-15. These relative deviations were determined on the basis of the predictive form of the equation and not the logarithmic form used in the regression.[6]

[6]If cost is estimated in a log-linear form such as

$$\ln \text{COST} = \beta_0 + \beta_1 \ln \text{WEIGHT} + \beta_2 \ln \text{SPEED} + \ln \varepsilon$$

the expected cost is given by

$$\text{COST} = \left( e^{\beta_0} \ \text{WEIGHT}^{\beta_1} \ \text{SPEED}^{\beta_2} \right) \times e^{\hat{\sigma}^2/2}$$

where $\hat{\sigma}^2$ is the actual variance of $\varepsilon$ in the log-linear equation. Since the actual variance is not known, the standard error of the estimate may be used as an approximation.

## III. SELECTION OF SET SIZE/PERFORMANCE COMBINATIONS

On the basis of a summary examination of all two-variable estimating relationships (size/performance) for all cost elements, it was decided to develop four distinct equation sets that maintain the integrity of the set size/performance parameters:

Airframe unit weight and speed
Airframe unit weight and climb rate
Empty weight and speed
Empty weight and climb rate

Generally speaking, the equations containing the size variable wetted area had higher standard errors of estimate than those equations containing airframe unit weight or empty weight. With respect to the performance parameters, the useful load variable was rarely found to be significant. On the other hand, estimating relationships containing the variable "speed class" were roughly comparable to those containing the variable "speed." However, given a choice, one would prefer to use a continuous variable. Therefore, speed class, since it offered no real advantage over speed, was not carried through as a set performance variable.

# IV. ENGINEERING

Engineering hours per pound are plotted as a function of airframe unit weight in Fig. 3. Estimating relationships in which all equation variables are significant at the 5 percent level are provided in Table 5.

## GENERAL OBSERVATIONS

1. With the exception of the four equations incorporating the number of black boxes (E13 - E16), the estimating relationships show a definite tendency to underestimate the engineering hours of the most recent sample aircraft.

2. The magnitude of the black box exponent in equations E13 through E16 seems somewhat excessive when applied to bomber/transport aircraft. That is, a 50 percent increase in the number of black boxes would increase total engineering hours by about 35 percent. Such a result may be reasonable for a fighter or attack aircraft with little available space but seems excessive for a large bomber or transport aircraft.

3. The magnitude of the contractor experience designator shows a great deal of variability depending on whether or not the black box variable is also included in the equation (E17, E19, and E20 compared with E23 through E25). Furthermore, in the first group (E17, E19, and E20) the exponent magnitude seems fairly large. For example, from equation E19, a contractor without experience would incur 75 percent more engineering hours than a contractor with experience.

4. The estimating relationships containing the program type designator (E18 and E21) indicate that a prototype development approach would require 30 percent fewer engineering hours than a concurrent development approach. Although one might expect prototype programs to incur somewhat less engineering because of their general emphasis on austerity, a difference of this magnitude seems excessive.

## REPRESENTATIVE CERS

### Airframe Unit Weight and Speed

Candidate estimating relationships are E4, E13, E17, E18, and E23. Equations E13, E17, E18, and E23 are eliminated for reasons of exponent magnitude. Unfortunately, the remaining equation (E4) shows a tendency to underestimate the most recent aircraft in the sample. However, since there are no other possibilities, E4 is selected as the representative AUW/SP estimating relationship for the engineering cost element:

$$E4\ ENGR_{100} = .00445\ \underset{(.000)}{AUW^{.758}}\ \underset{(.000)}{SP^{1.03}}$$

| $R^2$ | SEE | F | N | RP |
|---|---|---|---|---|
| .71 | .49 | 36 | 32 | CUR:UNDER |

### Airframe Unit Weight and Climb

Candidate estimating relationships are E6, E14, E19, and E24. Equations E14, E19, and E24 are eliminated for reasons of exponent magnitude. Thus, E6 is the representative AUW/CLIMB estimating relationship for the engineering cost element even though it shows a tendency to underestimate current aircraft:

$$E6\ ENGR_{100} = .0150\ \underset{(.000)}{AUW^{.830}}\ \underset{(.000)}{CLIMB^{.510}}$$

| $R^2$ | SEE | F | N | RP |
|---|---|---|---|---|
| .71 | .49 | 36 | 32 | CUR:UNDER |

### Empty Weight and Speed

Candidate estimating relationships are E7, E15, E20, E21, and E25. Equations E15, E20, E21, and E25 are eliminated for reasons of exponent magnitude. Unfortunately, the remaining equation (E7) shows a tendency to underestimate the most recent aircraft in the sample. However, since

there are no other possibilities, E7 is selected as the representative EW/SP estimating relationship:

$$\text{E7}\quad \text{ENGR}_{100} = .00355\ \underset{(.000)}{\text{EW}^{.787}}\ \underset{(.000)}{\text{SP}^{.980}}$$

| $R^2$ | SEE | F | N | RP |
|---|---|---|---|---|
| .70 | .50 | 34 | 32 | CUR:UNDER |

## Empty Weight and Climb

Candidate estimating relationships are E9, E16, and E22. Equations E16 and E22 are eliminated for reasons of exponent magnitude. Thus, E9 is the representative EW/CLIMB estimating relationship for the engineering cost element even though it shows a tendency to underestimate current aircraft:

$$\text{E9}\quad \text{ENGR}_{100} = .0100\ \underset{(.000)}{\text{EW}^{.862}}\ \underset{(.000)}{\text{CLIMB}^{.485}}$$

| $R^2$ | SEE | F | N | RP |
|---|---|---|---|---|
| .70 | .50 | 34 | 32 | CUR:UNDER |

## Single Best Estimating Relationship

Based on a summary examination of all 25 engineering equations, the list of candidate estimating relationships was narrowed to include the four equations discussed above plus E5 and E8. Of the six CERs, E5 and E8, which are essentially equivalent, have the lowest standard errors of estimate. Equation E5 is arbitrarily selected:

$$\text{E5}\quad \text{ENGR}_{100} = 3.26\ \underset{(.000)}{\text{AUW}^{.733}}\ \underset{(.000)}{\text{SPCLS}^{.925}}$$

| $R^2$ | SEE | F | N | RP |
|---|---|---|---|---|
| .74 | .46 | 42 | 32 | CUR:UNDER |

## SUMMARY

Each of the representative CERs shows a tendency to underestimate the engineering effort for the most recent aircraft in the sample. Furthermore, the standard errors of estimate for the representative CERs are all considerably greater than the goal of 0.18. Additionally, the exponents of the construction/program variables determined to be significant at the 5 percent level (number of black boxes, contractor experience designator, and program type designator) produce results that are not credible.

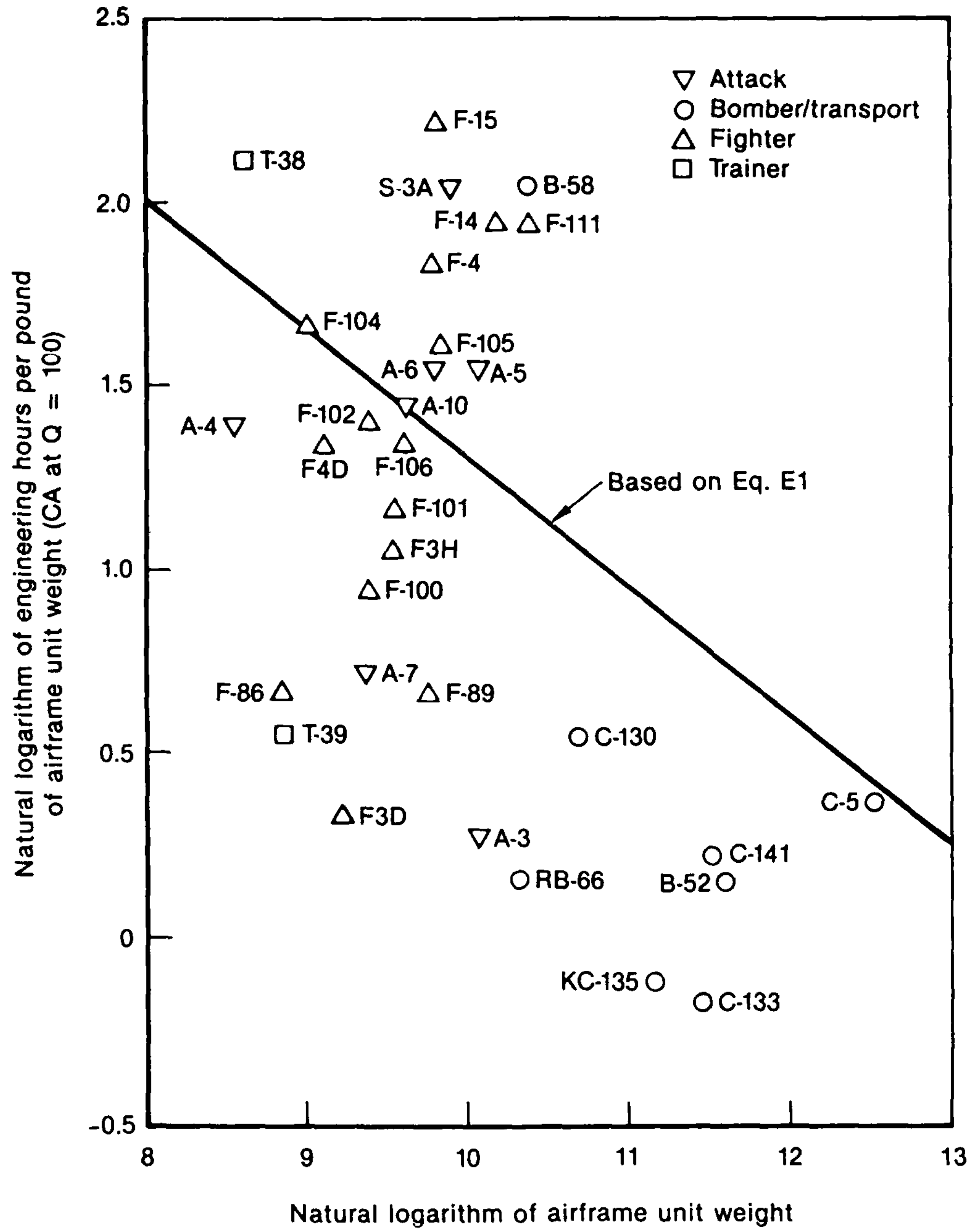



Fig. 3—Engineering hours per pound as a function of airframe unit weight

Table 5

ENGINEERING HOUR ESTIMATING RELATIONSHIPS

| Eq. No. | Equation | Statistics $R^2$ | SEE | F | N | Relative Deviations (%) A-10 | C-141 | F-14 | F-15 | Abs Avg | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **SIZE** | | | | | | | | | | |
| E1 | $ENGR_{100} = 11.5\ AUW^{.654}$ (.000)(a) | .48 | .65 | 28 | 32 | +1 | -69 | +52 | +58 | 45 | RP:CUR:UNDER |
| E2 | $ENGR_{100} = 5.72\ EW^{.697}$ (.000) | .49 | .64 | 29 | 32 | +8 | -68 | +53 | +57 | 46 | RP:CUR:UNDER |
| E3 | $ENGR_{100} = 73.9\ WTAREA^{.590}$ (.000) | .35 | .71 | 15 | 29 | -19 | -59 | +54 | +53 | 46 | RP:CUR:UNDER 10:C-5 |
| | **SIZE/PERFORMANCE** | | | | | | | | | | |
| E4 | $ENGR_{100} = .00445\ AUW^{.758}\ SP^{1.03}$ (.000) (.000) | .71 | .49 | 36 | 32 | +50 | -32 | +10 | +24 | 29 | RP:CUR:UNDER 10:S-3 |
| E5 | $ENGR_{100} = 3.26\ AUW^{.733}\ SPCLS^{.925}$ (.000) (.000) | .74 | .46 | 42 | 32 | +40 | -20 | +16 | +28 | 26 | RP:CUR:UNDER |
| E6 | $ENGR_{100} = .0150\ AUW^{.830}\ CLIMB^{.510}$ (.000) (.000) | .71 | .49 | 36 | 32 | +45 | -58 | +9 | +13 | 31 | RP:CUR:UNDER 10:S-3 |
| E7 | $ENGR_{100} = .00355\ EW^{.787}\ SP^{.980}$ (.000) (.000) | .70 | .50 | 34 | 32 | +52 | -30 | +15 | +24 | 30 | RP:CUR:UNDER 10:S-3 |

(a)Variable significance levels are in parentheses.

Table 5 (continued)

| Eq. No. | Equation | $R^2$ | SEE | F | N | A-10 | C-141 | F-14 | F-15 | Abs Avg | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Statistics | | | | Relative Deviations (%) | | | | | |
| E8 | $ENGR_{100} = 1.68\ EW^{.772}_{(.000)}\ SPCLS^{.904}_{(.000)}$ | .74 | .46 | 42 | 32 | +44 | -19 | +19 | +27 | 27 | RP:CUR:UNDER |
| E9 | $ENGR_{100} = .0100\ EW^{.862}_{(.000)}\ CLIMB^{.485}_{(.000)}$ | .70 | .50 | 34 | 32 | +48 | -55 | +15 | +13 | 33 | RP:CUR:UNDER<br>10:S-3 |
| E10 | $ENGR_{100} = .00510\ WTAREA^{.815}_{(.000)}\ SP^{1.17}_{(.000)}$ | .65 | .53 | 25 | 29 | +48 | -34 | +12 | +12 | 26 | RP:CUR:UNDER<br>10:S-3 |
| E11 | $ENGR_{100} = 11.0\ WTAREA^{.760}_{(.000)}\ SPCLS^{1.01}_{(.000)}$ | .68 | .51 | 27 | 29 | +34 | -19 | +20 | +19 | 23 | RP:CUR:UNDER |
| E12 | $ENGR_{100} = .0413\ WTAREA^{.865}_{(.000)}\ CLIMB^{.550}_{(.000)}$ | .61 | .56 | 20 | 29 | +38 | -63 | +14 | -1 | 29 | RP:CUR:UNDER<br>10:S-3 |
| | <u>SIZE/PERFORMANCE/CONSTRUCTION</u> | | | | | | | | | | |
| E13 | $ENGR_{100} = .0293\ AUW^{.466}_{(.000)}\ SP^{.906}_{(.000)}\ BLBOX^{.720}_{(.000)}$ | .84 | .38 | 46 | 31 | +38 | -40 | -8 | -14 | 25 | MCOL:r:(AUW) > .7<br>10:S-3<br>EXP MAG:BLBOX |
| E14 | $ENGR_{100} = .0754\ AUW^{.506}_{(.000)}\ CLIMB^{.465}_{(.000)}\ BLBOX^{.786}_{(.000)}$ | .85 | .37 | 50 | 31 | +34 | -62 | -13 | -35 | 36 | MCOL:r:(AUW) > .7<br>10:S-3<br>EXP MAG:BLBOX |

Table 5 (continued)

| Eq. No. | Equation | Statistics: $R^2$ | SEE | F | N | Relative Deviations (%): A-10 | C-141 | F-14 | F-15 | Abs Avg | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| E15 | $ENGR_{100} = .0272\ EW^{.474}\ SP^{.870}\ BLBOX^{.738}$ <br> (.000) (.000) (.000) | .83 | .39 | 44 | 31 | +40 | -39 | -4 | -15 | 24 | IO:A-7,S-3 <br> EXP MAG:BLBOX |
| E16 | $ENGR_{100} = .0613\ EW^{.520}\ CLIMB^{.449}\ BLBOX^{.798}$ <br> (.000) (.000) (.000) | .84 | .37 | 48 | 31 | +36 | -60 | -9 | -36 | 35 | MCOL:r:(AUW) > .7 <br> EXP MAG:BLBOX |
| | <u>SIZE/PERFORMANCE/PROGRAM</u> | | | | | | | | | | |
| E17 | $ENGR_{100} = .00142\ AUW^{.790}\ SP^{1.13}\ EXPDV^{.687}$ <br> (.000) (.000) (.003) | .78 | .44 | 33 | 32 | +39 | -10 | +21 | +34 | 26 | EXP MAG:EXPDV <br> RP:CUR:UNDER |
| E18 | $ENGR_{100} = .0499\ AUW^{.670}\ SP^{.822}\ PRGDV^{-.526}$ <br> (.000) (.001) (.044) | .74 | .47 | 27 | 32 | +53 | -44 | +10 | +21 | 32 | EXP MAG:PRGDV <br> RP:CUR:UNDER <br> IO:S-3 |
| E19 | $ENGR_{100} = .00324\ AUW^{.884}\ CLIMB^{.590}\ EXPDV^{.808}$ <br> (.000) (.000) (.001) | .80 | .42 | 38 | 32 | +31 | -30 | +20 | +23 | 26 | EXP MAG:EXPDV <br> RP:CUR:UNDER |
| E20 | $ENGR_{100} = .00104\ EW^{.825}\ SP^{1.08}\ EXPDV^{.708}$ <br> (.000) (.000) (.003) | .77 | .44 | 32 | 32 | +41 | -9 | +26 | +34 | 28 | EXP MAG:EXPDV <br> RP:CUR:UNDER |
| E21 | $ENGR_{100} = .0484\ EW^{.691}\ SP^{.758}\ PRGDV^{-.568}$ <br> (.000) (.002) (.034) | .73 | .48 | 26 | 32 | +55 | -44 | +15 | +21 | 34 | EXP MAG:EXPDV <br> IO:S-3A <br> RP:CUR:UNDER |

Table 5 (continued)

| Eq. No. | Equation | $R^2$ | SEE | F | N | A-10 | C-141 | F-14 | F-15 | Abs Avg | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Statistics | | | | Relative Deviations (%) | | | | | |
| E22 | $ENGR_{100} = .00193\ \underset{(.000)}{EW^{.924}}\ \underset{(.000)}{CLIMB^{.566}}\ \underset{(.001)}{EXPDV^{.830}}$ | .80 | .42 | 36 | 32 | +35 | -27 | +25 | +24 | 28 | EXP MAG:EXPDV<br>RP:CUR:UNDER |
| SIZE/PERFORMANCE/CONSTRUCTION/PROGRAM | | | | | | | | | | | |
| E23 | $ENGR_{100} = .0109\ \underset{(.000)}{AUW^{.527}}\ \underset{(.000)}{SP^{.985}}\ \underset{(.001)}{BLBOX^{.617}}\ \underset{(.022)}{EXPDV^{.434}}$ | .86 | .36 | 40 | 31 | +32 | -24 | +3 | +2 | 15 | MCOL:r(AUW) > .7<br>RP:CUR:UNDER<br>EXP MAG:BLBOX |
| F24 | $ENGR_{100} = .0195\ \underset{(.000)}{AUW^{.595}}\ \underset{(.000)}{CLIMB^{.531}}\ \underset{(.000)}{BLBOX^{.660}}\ \underset{(.003)}{EXPDV^{.555}}$ | .88 | .33 | 50 | 31 | +26 | -40 | 0 | -16 | 20 | MCOL:r(AUW) > .7<br>RP:CUR:UNDER<br>EXP MAG:BLBOX |
| E25 | $ENGR_{100} = .00940\ \underset{(.000)}{EW^{.543}}\ \underset{(.000)}{SP^{.947}}\ \underset{(.000)}{BLBOX^{.631}}\ \underset{(.022)}{EXPDV^{.443}}$ | .85 | .37 | 38 | 31 | +33 | -23 | +7 | +1 | 16 | MCOL:r(AUW) > .7<br>RP:CUR:UNDER<br>EXP MAG:BLBOX |

# V. TOOLING

Tooling hours per pound are plotted as a function of airframe unit weight in Fig. 4. Estimating relationships in which all equation variables are significant at the 5 percent level are provided in Table 6.

## GENERAL OBSERVATIONS

1. In general, the estimating relationships have relatively high standard errors of estimate, but on the other hand, they are relatively free of residual patterns.

2. The magnitude of the engine location variable seems high. Equations T13 and T14 indicate that an aircraft with engines mounted in nacelles under the wing will incur 40 percent to 50 percent more tooling hours than an aircraft with engines embedded in the fuselage.

3. Other than the engine location variable, no construction/program variables were found significant at the 5 percent level in any of the prescribed variable combinations.

## REPRESENTATIVE CERS

### Airframe Unit Weight and Speed

Candidate estimating relationships are T4 and T13. Equation T13 is eliminated for reasons of exponent magnitude. Equation T4 is preferred:

| Equation | $R^2$ | SEE | F | N | RP |
|---|---|---|---|---|---|
| T4 $TOOL_{100} = .127\ AUW^{.699}\ SP^{.609}$ <br> (.000) (.001) | .74 | .40 | 41 | 32 | None |

## Airframe Unit Weight and Climb

The only candidate estimating relationship is T6:

$$\text{T6 } TOOL_{100} = .502\ AUW^{.724}\ CLIMB^{.249}$$
$$(.000)\quad(.005)$$

| $R^2$ | SEE | F | N | RP |
|---|---|---|---|---|
| .70 | .43 | 34 | 32 | None |

## Empty Weight and Speed

Candidate estimating relationships are T7 and T14. Equation T14 is eliminated for reasons of exponent magnitude. Equation T8 is preferred:

$$\text{T7 } TOOL_{100} = .0695\ EW^{.755}\ SP^{.570}$$
$$(.000)(.001)$$

| $R^2$ | SEE | F | N | RP |
|---|---|---|---|---|
| .78 | .37 | 52 | 32 | None |

## Empty Weight and Climb

The only candidate estimating relationship is T9:

$$\text{T9 } TOOL_{100} = .227\ EW^{.784}\ CLIMB^{.238}$$
$$(.000)\quad(.004)$$

| $R^2$ | SEE | F | N | RP |
|---|---|---|---|---|
| .75 | .39 | 44 | 32 | None |

## Single Best Estimating Relationship

Based on a summary examination of all 14 tooling equations, the list of candidate estimating relationships has been narrowed to the four equations discussed above. Of these equations, T7 has the lowest standard error of estimate:

$$T7\ TOOL_{100} = .0695\ \underset{(.000)}{EW^{.755}}\ \underset{(.001)}{SP^{.570}}$$

| $R^2$ | SEE | F | N | RP |
|---|---|---|---|---|
| .78 | .37 | 52 | 32 | None |

## SUMMARY

The standard errors of estimate of the representative CERs are roughly double the goal of 0.18. Additionally, the exponent of the construction/program variable found to be significant at the 5 percent level (engine location designator) produces results that are not credible.

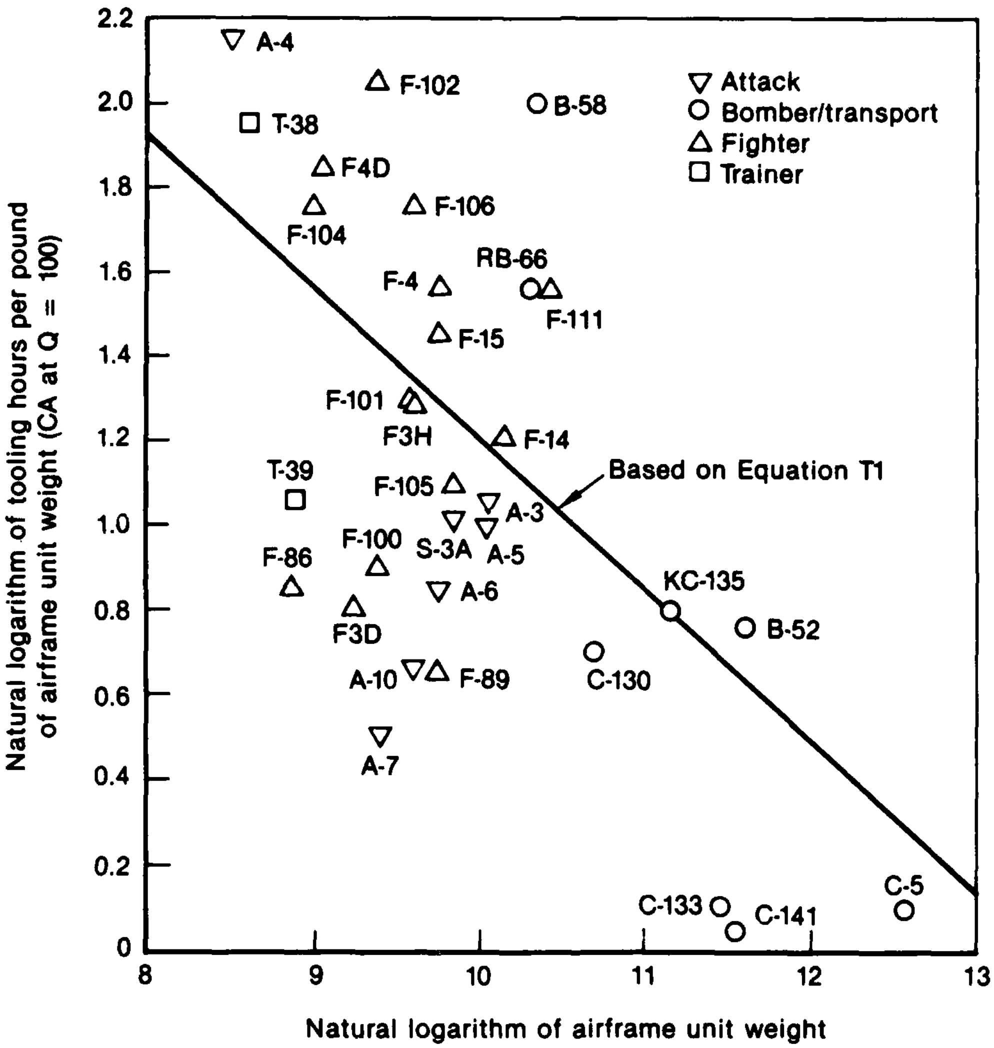



Fig. 4—Tooling hours per pound as a function of airframe unit weight

Table 6

TOOLING HOUR ESTIMATING RELATIONSHIPS

| Eq. No. | Equation | Statistics | | | | Relative Deviations (%) | | | | | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $R^2$ | SEE | F | N | A-10 | C-141 | F-14 | F-15 | Abs Avg | |
| | SIZE | | | | | | | | | | |
| T1 | $TOOL_{100} = 12.6\ \underset{(.000)}{AUW^{.638}}$ | .63 | .47 | 50 | 32 | -103 | -88 | +6 | +14 | 53 | |
| T2 | $TOOL_{100} = 4.98\ \underset{(.000)}{EW^{.703}}$ | .68 | .43 | 65 | 32 | -84 | -91 | +9 | +13 | 49 | IO:B-58,C-141 |
| T3 | $TOOL_{100} = 39.2\ \underset{(.000)}{WTAREA^{.655}}$ | .59 | .48 | 39 | 29 | -130 | -92 | +14 | +8 | 61 | IO:C-141,F-86 |
| | SIZE/PERFORMANCE | | | | | | | | | | |
| T4 | $TOOL_{100} = .127\ \underset{(.000)}{AUW^{.699}}\ \underset{(.001)}{SP^{.609}}$ | .74 | .40 | 41 | 32 | -39 | -66 | -39 | -25 | 42 | |
| T5 | $TOOL_{100} = 6.62\ \underset{(.000)}{AUW^{.681}}\ \underset{(.001)}{SPCLS^{.492}}$ | .73 | .41 | 39 | 32 | -60 | -61 | -30 | -18 | 42 | IO:A-4,B-58 |
| T6 | $TOOL_{100} = .502\ \underset{(.000)}{AUW^{.724}}\ \underset{(.005)}{CLIMB^{.249}}$ | .70 | .43 | 34 | 32 | -56 | -86 | -31 | -26 | 50 | |
| T7 | $TOOL_{100} = .0695\ \underset{(.000)}{EW^{.755}}\ \underset{(.001)}{SP^{.570}}$ | .78 | .37 | 52 | 32 | -29 | -68 | -31 | -24 | 38 | |
| T8 | $TOOL_{100} = 2.67\ \underset{(.000)}{EW^{.743}}\ \underset{(.001)}{SPCLS^{.480}}$ | .78 | .37 | 52 | 32 | -46 | -63 | -25 | -18 | 38 | |

Table 6 (continued)

| Eq. No. | Equation | Statistics $R^2$ | SEE | F | N | Relative Deviations (%) A-10 | C-141 | F-14 | F-15 | Abs Avg | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| T9 | $TOOL_{100} = .227\ \underset{(.000)}{EW^{.784}}\ \underset{(.004)}{CLIMB^{.238}}$ | .75 | .39 | 44 | 32 | -42 | -88 | -24 | -25 | 45 | |
| T10 | $TOOL_{100} = .0649\ \underset{(.000)}{WTAREA^{.806}}\ \underset{(.000)}{SP^{.786}}$ | .78 | .36 | 45 | 29 | -35 | -76 | -3[illegible] | -42 | 47 | |
| T11 | $TOOL_{100} = 13.0\ \underset{(.000)}{WTAREA^{.756}}\ \underset{(.000)}{SPCLS^{.597}}$ | .75 | .39 | 39 | 29 | -68 | -67 | -24 | -30 | 47 | |
| T12 | $TOOL_{100} = .524\ \underset{(.000)}{WTAREA^{.815}}\ \underset{(.002)}{CLIMB^{.318}}$ | .71 | .42 | 32 | 29 | -61 | -99 | -27 | -45 | 58 | |
| | <u>SIZE/PERFORMANCE/CONSTRUCTION</u> | | | | | | | | | | |
| T13 | $TOOL_{100} = .0749\ \underset{(.000)}{AUW^{.584}}\ \underset{(.000)}{SP^{.841}}\ \underset{(.034)}{ENGLOC^{.611}}$ | .77 | .38 | 31 | 32 | -64 | -66 | -34 | -26 | 48 | MCOL: r(ENGLOC) > .7<br>RP:CUR:OVER<br>EXP MAG:ENGLOC |
| T14 | $TOOL_{100} = .0470\ \underset{(.000)}{EW^{.651}}\ \underset{(.000)}{SP^{.774}}\ \underset{(.046)}{ENGLOC^{.520}}$ | .80 | .35 | 38 | 32 | -50 | -68 | -28 | -25 | 43 | MCOL: r(ENGLOC) > .7<br>EXP MAG:ENGLOC |
| | <u>SIZE/PERFORMANCE/PROGRAM</u> | | | | | | | | | | |
| | None | | | | | | | | | | |
| | <u>SIZE/PERFORMANCE/CONSTRUCTION/PROGRAM</u> | | | | | | | | | | |
| | None | | | | | | | | | | |

# VI. MANUFACTURING LABOR

Manufacturing labor hours per pound are plotted as a function of airframe unit weight in Fig. 5. Estimating relationships in which all equation variables are significant at the 5 percent level are provided in Table 7.

## GENERAL OBSERVATIONS

1. Generally speaking, the total sample estimating relationships represent reasonably good fits and are, with one exception, free of residual patterns.

2. As adjuncts to various combinations of size and performance variables, two construction/program variables (EWAUW and TOOLCP) were determined to be significant at the 5 percent level. However, only one of them (EWAUW) was also found to be significant in a more limited analysis of 11 post-1960 aircraft. And even the EWAUW variable had difficulties--its exponent in the post-1960 analysis increased by a factor of two over the full 32-aircraft sample.

## REPRESENTATIVE CERS

### Airframe Unit Weight and Speed

Candidate estimating relationships are L4, L13, and L16. Equations L13 and L16 are eliminated because of the previously alluded to variability in the EWAUW exponent between the total and post-1960 samples. That leaves equation L4:

$$\text{L4 } LABR_{100} = .329\, AUW^{.801}\, SP^{.429}$$

$$(.000)\quad(.002)$$

| $R^2$ | SEE | F | N | RP |
|---|---|---|---|---|
| .86 | .31 | 88 | 32 | None |

### Airframe Unit Weight and Climb

Candidate estimating relationships are L6, L14, and L17. Equations L14 and L17 are eliminated because of the previously alluded to variability in the EWAUW exponent between the total and post-1960 samples. That leaves equation L6:

$$L6 \quad LABR_{100} = .757\ AUW^{.822}_{(.000)}\ CLIMB^{.186}_{(.006)}$$

| $R^2$ | SEE | F | N | RP |
|---|---|---|---|---|
| .85 | .32 | 80 | 32 | None |

### Empty Weight and Speed

Candidate estimating relationship are L7 and L15. L15 is eliminated from consideration because the variable TOOLCP was not also significant in the more limited analysis of post-1960 aircraft. That leaves L7:

$$L7 \quad LABR_{100} = .198\ EW^{.852}_{(.000)}\ SP^{.379}_{(.002)}$$

| $R^2$ | SEE | F | N | RP |
|---|---|---|---|---|
| .88 | .28 | 109 | 32 | None |

### Empty Weight and Climb

The only candidate estimating relationship is L9:

$$L9 \quad LABR_{100} = .383\ EW^{.874}_{(.000)}\ CLIMB^{.168}_{(.005)}$$

| $R^2$ | SEE | F | N | RP |
|---|---|---|---|---|
| .87 | .29 | 101 | 32 | None |

## Single Best Estimating Relationship

Based on a summary examination of all 17 manufacturing labor equations, the list of candidate estimating relationships has been narrowed to include the four equations discussed above plus L5 and L8. Generally speaking, all possess approximately the same standard error of estimate. Equation L7 is arbitrarily selected.

$$\text{L7 } LABR_{100} = .198\, EW^{.852}\, SP^{.379}$$
$$(.000)(.002)$$

| $R^2$ | SEE | F | N | RP |
|---|---|---|---|---|
| .88 | .28 | 109 | 32 | None |

## SUMMARY

The standard errors of estimate for the representative CERs are all somewhat higher than the goal of 0.18. Additionally, although several construction/program variables were found to be significant at the 5 percent level (as adjuncts to various size/performance combinations), each had difficulties that we felt precluded its incorporation in a recommended CER.

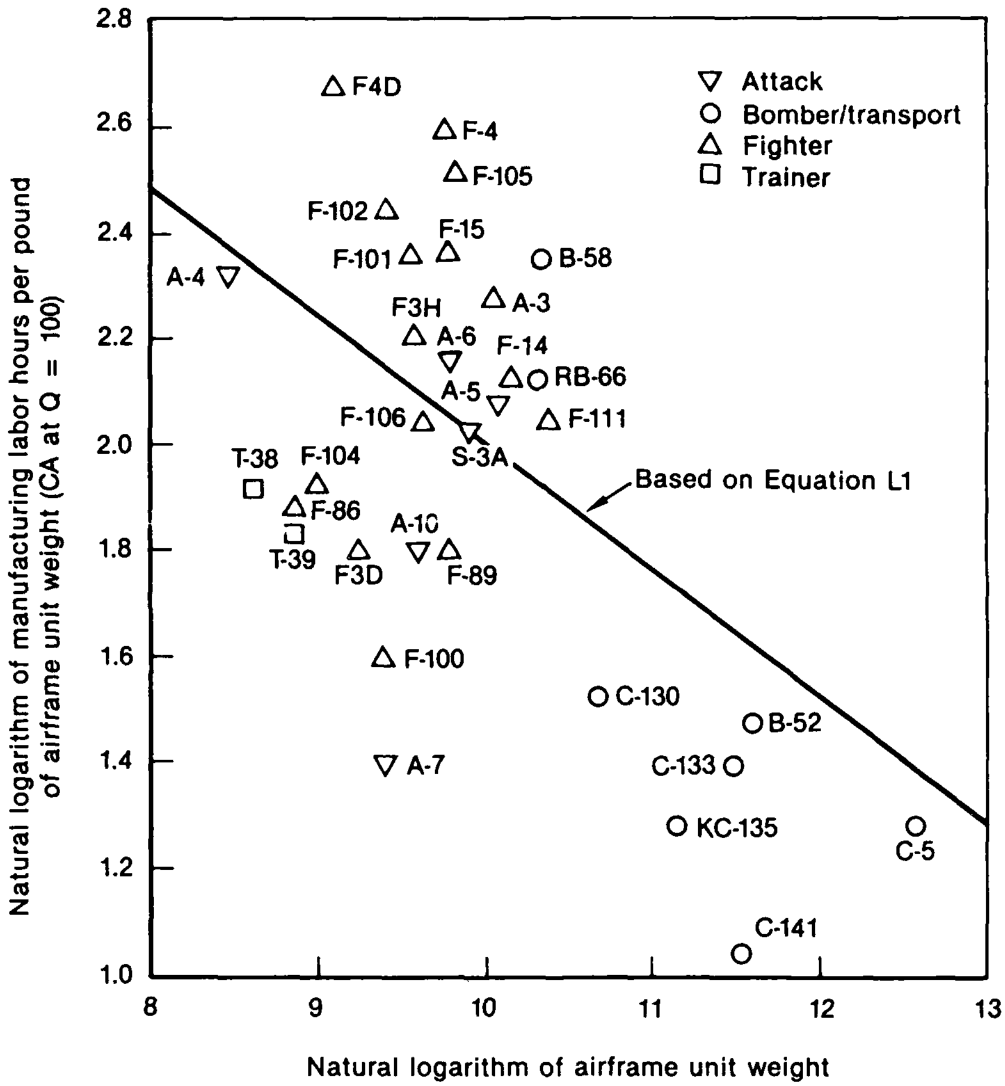



Fig. 5—Manufacturing labor hours per pound as a function of airframe unit weight

Table 7

MANUFACTURING LABOR HOUR ESTIMATING RELATIONSHIPS

| Eq. No. | Equation | Statistics $R^2$ | SEE | F | N | Relative Deviations (%) A-10 | C-141 | F-14 | F-15 | Abs Avg | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | SIZE | | | | | | | | | | |
| L1 | $LABR_{100} = 8.37\ AUW^{.758}$ (.000) | .81 | .35 | 126 | 32 | -34 | -77 | +14 | +25 | 38 | 10:C-141 |
| L2 | $LABR_{100} = 3.39\ EW^{.817}$ (.000) | .84 | .32 | 160 | 32 | -21 | -77 | +16 | +23 | 34 | 10:C-141 |
| L3 | $LABR_{100} = 49.2\ WTAREA^{.727}$ (.000) | .72 | .40 | 70 | 29 | -59 | -71 | +21 | +17 | 42 | 10:C-141 |
| | SIZE/PERFORMANCE | | | | | | | | | | |
| L4 | $LABR_{100} = .329\ AUW^{.801}\ SP^{.429}$ (.000) (.002) | .86 | .31 | 88 | 32 | -3 | -64 | -15 | +2 | 21 | |
| L5 | $LABR_{100} = 5.61\ AUW^{.785}\ SPCLS^{.313}$ (.000) (.006) | .85 | .32 | 80 | 32 | -16 | -62 | -7 | +8 | 23 | |
| L6 | $LABR_{100} = .757\ AUW^{.822}\ CLIMB^{.186}$ (.000) (.006) | .85 | .32 | 80 | 32 | -10 | -77 | -11 | 0 | 24 | |
| L7 | $LABR_{100} = .198\ EW^{.852}\ SP^{.379}$ (.000) (.002) | .88 | .28 | 109 | 32 | +4 | -64 | -7 | +2 | 19 | |
| L8 | $LABR_{100} = 2.33\ EW^{.841}\ SPCLS^{.295}$ (.000) (.004) | .88 | .29 | 103 | 32 | -6 | -62 | -2 | +7 | 19 | |
| L9 | $LABR_{100} = .383\ EW^{.874}\ CLIMB^{.168}$ (.000) (.005) | .87 | .29 | 101 | 32 | -2 | -76 | -5 | 0 | 21 | |

Table 7 (continued)

| Eq. No. | Equation | $R^2$ | SEE | F | N | A-10 | C-141 | F-14 | F-15 | Abs Avg | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Statistics | | | | Relative Deviations (%) | | | | | |
| L10 | $LABR_{100} = .396\ \underset{(.000)}{WTAREA^{.841}}\ \underset{(.000)}{SP^{.593}}$ | .83 | .32 | 62 | 29 | -7 | -62 | -13 | -16 | 24 | |
| L11 | $LABR_{100} = 21.6\ \underset{(.000)}{WTAREA^{.803}}\ \underset{(.001)}{SPCLS^{.449}}$ | .81 | .34 | 55 | 29 | -27 | -55 | -5 | -9 | 24 | |
| L12 | $LABR_{100} = 1.42\ \underset{(.000)}{WTAREA^{.858}}\ \underset{(.002)}{CLIMB^{.262}}$ | .80 | .35 | 52 | 29 | -20 | -77 | -10 | -22 | 32 | |
| | <u>SIZE/PERFORMANCE/CONSTRUCTION</u> | | | | | | | | | | |
| L13 | $LABR_{100} = .359\ \underset{(.000)}{AUW^{.880}}\ \underset{(.007)}{SP^{.344}}\ \underset{(.015)}{EWAUW^{.388}}$ | .88 | .29 | 69 | 32 | +5 | -66 | -5 | +2 | 20 | IO:F-105 |
| L14 | $LABR_{100} = .628\ \underset{(.000)}{AUW^{.908}}\ \underset{(.012)}{CLIMB^{.153}}\ \underset{(.008)}{EWAUW^{.435}}$ | .88 | .29 | 66 | 32 | +2 | -77 | -3 | -1 | 21 | RP:CUR:UNDER IO:F-105 |
| | <u>SIZE/PERFORMANCE/PROGRAM</u> | | | | | | | | | | |
| L15 | $LABR_{100} = .471\ \underset{(.000)}{EW^{.782}}\ \underset{(.001)}{SP^{.412}}\ \underset{(.048)}{TOOLCP^{-.138}}$ | .89 | .27 | 78 | 32 | +5 | -54 | -16 | -2 | 19 | |
| | <u>SIZE/PERFORMANCE/CONSTRUCTION/PROGRAM</u> | | | | | | | | | | |
| L16 | $LABR_{100} = 1.17\ \underset{(.000)}{AUW^{.806}}\ \underset{(.003)}{SP^{.359}}\ \underset{(.004)}{EWAUW^{.480}}\ \underset{(.018)}{TOOLCP^{-.185}}$ | .90 | .27 | 60 | 32 | +8 | -52 | -13 | -4 | 19 | IO:F-105 |
| L17 | $LABR_{100} = 2.06\ \underset{(.000)}{AUW^{.832}}\ \underset{(.005)}{CLIMB^{.170}}\ \underset{(.001)}{EWAUW^{.531}}\ \underset{(.014)}{TOOLCP^{-.200}}$ | .90 | .27 | 59 | 32 | +6 | -61 | -12 | -9 | 22 | IO:F-105 |

# VII. MANUFACTURING MATERIAL

Manufacturing material cost per pound is plotted as a function of airframe unit weight in Fig. 6. Estimating relationships in which all equation variables are significant at the 5 percent level are provided in Table 8.

## GENERAL OBSERVATIONS

1. With the exception of the four equations incorporating the number of black boxes (M14, M16, M18, and M19), there is a definite tendency for the material costs of the most recent sample aircraft to be underestimated.

2. Equations M14, M16, M18, and M19 indicate that a 50 percent increase in the number of black boxes would result in a roughly 20 percent increase in total airframe material costs. This large an increase seems somewhat excessive.

3. The magnitude of the engine location variable also seems high. Equations M13 and M17 indicate that an aircraft with engines mounted in nacelles under the wing will incur roughly 45 percent higher material costs than an aircraft with engines embedded in the fuselage.

4. The contractor experience designator in equations M20, M21, and M22 indicate that a contractor with experience will incur 30 percent to 35 percent lower material costs than a contractor without experience, a result that is possible but not particularly credible.

## REPRESENTATIVE CERS

### Airframe Unit Weight and Speed

Candidate estimating relationships are M4, M13, M14, and M20. Equations M13, M14, and M20 are eliminated for reasons of exponent magnitude. Unfortunately, the remaining equation (M4) shows a tendency to underestimate the most recent aircraft in the sample. However, since there are no other possibilities, M4 is selected as the representative AUW/SP estimating relationship:

$$\text{M4 } \frac{\text{MATL}}{100} = .0999\ \text{AUW}^{.895}\ \text{SP}^{.811}$$
$$(.000)\quad(.000)$$

| $R^2$ | SEE | F | N | RP |
| --- | --- | --- | --- | --- |
| .84 | .38 | 77 | 32 | CUR:UNDER |

## Airframe Unit Weight and Climb

Candidate estimating relationships are M6, M15, and M16. Equations M15 and M16 are eliminated for reasons of exponent magnitude. Unfortunately, the remaining equation (M6) shows a tendency to underestimate the most recent aircraft in the sample. However, since there are no other possibilities, M6 is selected as the representative AUW/CLIMB estimating relationship:

$$\text{M6 } \frac{\text{MATL}}{100} = .686\ \text{AUW}^{.927}\ \text{CLIMB}^{.325}$$
$$(.000)\quad(.001)$$

| $R^2$ | SEE | F | N | RP |
| --- | --- | --- | --- | --- |
| .79 | .43 | 56 | 32 | CUR:UNDER |

## Empty Weight and Speed

Candidate estimating relationships are M7, M17, M18, and M21. Equations M17, M18, and M21 are eliminated for reasons of exponent magnitude. Unfortunately, the remaining equation (M7) shows a tendency to underestimate the most recent aircraft in the sample. However, since there are no other possibilities, M7 is selected as the representative EW/SP estimating relationship:

$$\text{M7 } \frac{\text{MATL}}{100} = .0623\ \text{EW}^{.945}\ \text{SP}^{.752}$$
$$(.000)(.000)$$

| $R^2$ | SEE | F | N | RP |
| --- | --- | --- | --- | --- |
| .85 | .36 | 83 | 32 | CUR:UNDER |

## Empty Weight and Climb

Candidate estimating relationships are M9, M19, and M22. Equations M19 and M22 are eliminated for reasons of exponent magnitude. Unfortunately, the remaining equation (M9) shows a tendency to underestimate the most recent aircraft in the sample. However, since there are no other possibilities, M9 is selected as the representative EW/CLIMB estimating relationship:

$$\text{M9}\quad MATL_{100} = .345\ \underset{(.000)}{EW^{.980}}\ \underset{(.001)}{CLIMB^{.303}}$$

| $R^2$ | SEE | F | N | RP |
|---|---|---|---|---|
| .85 | .36 | 85 | 32 | CUR:UNDER |

## Single Best Estimating Relationship

Based on a summary examination of all 22 manufacturing material equations, the list of candidate estimating relationships has been narrowed to the four equations discussed above. Of these equations, M4, M7, and M9 have the lowest standard errors of estimate. Equation M7 is arbitrarily selected:

$$\text{M7}\quad MATL_{100} = .0623\ \underset{(.000)}{EW^{.945}}\ \underset{(.000)}{SP^{.752}}$$

| $R^2$ | SEE | F | N | RP |
|---|---|---|---|---|
| .85 | .36 | 83 | 32 | CUR:UNDER |

## SUMMARY

The standard errors of estimate for the representative CERs are roughly double the goal of 0.18. Furthermore, the equations in which construction/program variables were found to be significant at the 5 percent level had difficulties associated with exponent magnitude and residual patterns.

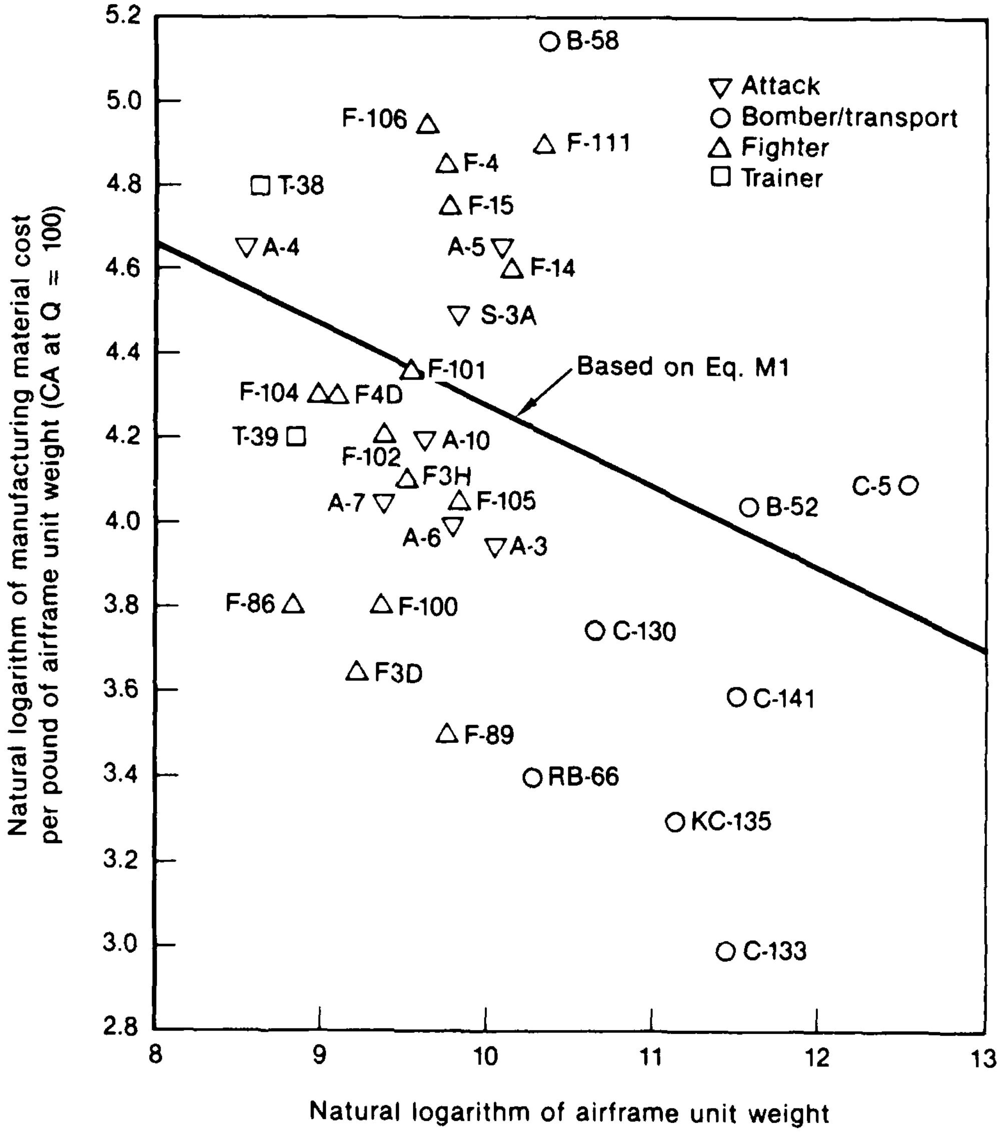



Fig. 6—Manufacturing material cost per pound as a function of airframe unit weight

Table 8

MANUFACTURING MATERIAL COST ESTIMATING RELATIONSHIPS

| Eq. No. | Equation | Statistics $R^2$ | SEE | F | N | Relative Deviations (%) A-10 | C-141 | F-14 | F-15 | Abs Avg | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | SIZE | | | | | | | | | | |
| M1 | $MATL_{100} = 46.2\ AUW^{.814}$ (.000) | .70 | .50 | 72 | 32 | -16 | -46 | +31 | +34 | 32 | RP:CUR:UNDER<br>IO:C-5,C-133 |
| M2 | $MATL_{100} = 17.7\ EW^{.877}$ (.000) | .73 | .48 | 82 | 32 | -4 | -46 | +34 | +33 | 29 | RP:CUR:UNDER<br>IO:C-5,C-133,KC-135 |
| M3 | $MATL_{100} = 225\ WTAREA^{.821}$ (.000) | .62 | .57 | 44 | 29 | -38 | -48 | +38 | +28 | 38 | RP:CUR:UNDER<br>IO:C-5,C-133,KC-135 |
| | SIZE/PERFORMANCE | | | | | | | | | | |
| M4 | $MATL_{100} = .0999\ AUW^{.895}\ SP^{.811}$ (.000) (.000) | .84 | .38 | 77 | 32 | +31 | -22 | -14 | -6 | 18 | IO:C-5<br>RP:CUR:UNDER |
| M5 | $MATL_{100} = 19.2\ AUW^{.871}\ SPCLS^{.662}$ (.000) (.000) | .83 | .38 | 73 | 32 | +17 | -17 | -6 | +1 | 10 | RP:CUR:UNDER<br>IO:C-5 |
| M6 | $MATL_{100} = .686\ AUW^{.927}\ CLIMB^{.325}$ (.000) (.001) | .79 | .43 | 56 | 32 | +19 | -43 | -6 | -7 | 19 | RP:CUR:UNDER |
| M7 | $MATL_{100} = .0623\ EW^{.945}\ SP^{.752}$ (.000) (.000) | .85 | .36 | 83 | 32 | +36 | -22 | -6 | -6 | 18 | RP:CUR:UNDER<br>IO:C-5 |
| M8 | $MATL_{100} = 7.61\ EW^{.929}\ SPCLS^{.641}$ (.000) (.000) | .85 | .36 | 85 | 32 | +25 | -16 | 0 | 0 | 10 | RP:CUR:UNDER<br>IO:C-5 |

Table 8 (continued)

| Eq. No. | Equation | $R^2$ | SEE | F | N | A-10 | C-141 | F-14 | F-15 | Abs Avg | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Statistics | | | | Relative Deviations (%) | | | | | |
| M9 | $MATL_{100} = .345\ EW^{.980}\ CLIMB^{.303}$ <br> (.000) (.001) | .81 | .41 | 62 | 32 | +26 | -41 | +2 | -6 | 19 | RP:CUR:UNDER <br> IO:C-5 |
| M10 | $MATL_{100} = .0370\ WTAREA^{1.03}\ SP^{1.07}$ <br> (.000) (.000) | .85 | .37 | 72 | 29 | +35 | -28 | -14 | -28 | 26 | IO:C-5,S-3 <br> EXP MAG:WTAREA |
| M11 | $MATL_{100} = 48.2\ WTAREA^{.960}\ SPCLS^{.821}$ <br> (.000) (.000) | .82 | .40 | 58 | 29 | +13 | -20 | -1 | -14 | 12 | RP:CUR:UNDER <br> IO:C-5 |
| M12 | $MATL_{100} = .629\ WTAREA^{1.04}\ CLIMB^{.432}$ <br> (.000) (.000) | .76 | .46 | 42 | 29 | +16 | -54 | -4 | -33 | 27 | RP:CUR:UNDER <br> EXP MAG:WTAREA |
| | <u>SIZE/PERFORMANCE/CONSTRUCTION</u> | | | | | | | | | | |
| M13 | $MATL_{100} = .0615\ AUW^{.789}\ SP^{1.02}\ ENGLOC^{.564}$ <br> (.000) (.000) (.036) | .86 | .36 | 57 | 32 | +20 | -22 | -10 | -8 | 15 | EXP MAG:ENGLOC <br> MCOL:r(ENGLOC) > .7 <br> RP:CUR:UNDER <br> IO:C-5 |
| M14 | $MATL_{100} = .343\ AUW^{.712}\ SP^{.723}\ BLBOX^{.459}$ <br> (.000) (.000) (.001) | .90 | .31 | 77 | 31 | +20 | -30 | -30 | -39 | 30 | MCOL:r(ENGLOC) > .7 <br> IO:C-5 <br> EXP MAG:BLBOX |
| M15 | $MATL_{100} = .443\ AUW^{1.07}\ CLIMB^{.292}\ AVAUW^{.259}$ <br> (.000) (.001) (.017) | .86 | .36 | 48 | 27 | +34 | -29 | -12 | 0 | 19 | RP:CUR:UNDER <br> EXP MAG:AUW |
| M16 | $MATL_{100} = 2.20\ AUW^{.711}\ CLIMB^{.288}\ BLBOX^{.525}$ <br> (.000) (.001) (.002) | .86 | .37 | 54 | 31 | +6 | -49 | -23 | -44 | 30 | MCOL:r(AUW) > .7 <br> IO:C-5 <br> EXP MAG:BLBOX |

Table 8 (continued)

| Eq. No. | Equation | $R^2$ | SEE | F | N | A-10 | C-141 | F-14 | F-15 | Abs Avg | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Statistics | | | | Relative Deviations (%) | | | | | |
| M17 | $MATL_{100} = .0422\ EW^{.841}\ SP^{.956}\ ENGLOC^{.520}$ <br> (.000) (.000) (.045) | .87 | .35 | 60 | 32 | +25 | -22 | -4 | -7 | 14 | EXP MAG:ENGLOC <br> MCOL:r(ENGLOC) > .7 <br> RP:CUR:UNDER <br> IO:C-5 |
| M18 | $MATL_{100} = .226\ EW^{.755}\ SP^{.677}\ BLBOX^{.455}$ <br> (.000) (.000) (.001) | .90 | .30 | 86 | 31 | +24 | -29 | -22 | -37 | 28 | EXP MAG:BLBOX <br> IO:C-5 |
| M19 | $MATL_{100} = 1.20\ EW^{.761}\ CLIMB^{.272}\ BLBOX^{.510}$ <br> (.000) (.001) (.001) | .87 | .35 | 61 | 31 | +12 | -48 | -16 | -42 | 30 | MCOL:r(EW) > .7 <br> IO:C-5 <br> EXP MAG:BLBOX |
| | <u>SIZE/PERFORMANCE/PROGRAM</u> | | | | | | | | | | |
| M20 | $MATL_{100} = .0546\ AUW^{.913}\ SP^{.861}\ EXPDV^{.370}$ <br> (.000) (.000) (.033) | .86 | .36 | 57 | 32 | +23 | -12 | -7 | +1 | 11 | RP:CUR:UNDER <br> IO:C-5 <br> EXP MAG:EXPDV |
| M21 | $MATL_{100} = .0315\ EW^{.967}\ SP^{.806}\ EXPDV^{.399}$ <br> (.000) (.000) (.019) | .87 | .34 | 64 | 32 | +27 | -11 | +1 | +2 | 10 | RP:CUR:UNDER <br> IO:C-5 <br> EXP MAG:EXPDV |
| M22 | $MATL_{100} = .145\ EW^{1.01}\ CLIMB^{.346}\ EXPDV^{.443}$ <br> (.000) (.000) (.023) | .84 | .39 | 48 | 32 | +15 | +28 | +7 | 0 | 12 | RP:CUR:UNDER <br> EXP MAG:EW <br> EXP MAG:EXPDV |
| | <u>SIZE/PERFORMANCE/CONSTRUCTION/PROGRAM</u> | | | | | | | | | | |
| | None | | | | | | | | | | |

# VIII. DEVELOPMENT SUPPORT

Development support cost per pound is plotted as a function of airframe unit weight in Fig. 7. Estimating relationships in which all equation variables are significant at the 5 percent level are provided in Table 9.

## GENERAL OBSERVATIONS

1. None of the estimating relationships listed in Table 14 comes close to meeting the standard error of estimate goal of 0.18. Furthermore, there is a definite tendency for the development support costs of the most recent sample aircraft to be underestimated.

2. As adjuncts to various combinations of size and performance variables, several construction/program variables were determined to be significant at the 5 percent level. However, they provide relatively modest, if any, improvement in the equation standard error of estimate.

3. Equations D13, D15, D16, and D19 indicate that a 50 percent increase in the ratio of avionics weight to airframe unit weight will result in a 25 percent to 30 percent increase in development support cost. Similarly, equations D14 and D17 indicate that a 50 percent increase in the number of black boxes will result in a 35 percent increase in development support cost. In both instances, such differences seem excessive.

4. The estimating relationships containing the program type designator (D20, D21, and D22) indicate that a prototype development approach would incur about 40 percent as much development support cost as a concurrent development approach. Such a difference is not credible.

# REPRESENTATIVE CERS

## Airframe Unit Weight and Speed

Candidate estimating relationships are D4, D13, D14, and D20. All but equation D4 are eliminated for reasons of exponent magnitude. Unfortunately, equation D4 shows a tendency to underestimate the most recent aircraft in the sample.

$$\text{D4}\quad DS = .00761\ \underset{(.000)}{AUW^{.761}}\ \underset{(.001)}{SP^{1.28}}$$

| $R^2$ | SEE | F | N | RP |
|---|---|---|---|---|
| .50 | .82 | 15 | 32 | CUR:UNDER |

## Airframe Unit Weight and Climb

Candidate estimating relationships are D6 and D15. Equation D15 is eliminated for reasons of exponent magnitude. Unfortunately, equation D6 shows a tendency to underestimate the most recent aircraft in the sample.

$$\text{D6}\quad DS = .0780\ \underset{(.000)}{AUW^{.829}}\ \underset{(.002)}{CLIMB^{.567}}$$

| $R^2$ | SEE | F | N | RP |
|---|---|---|---|---|
| .46 | .85 | 12 | 32 | CUR:UNDER |

## Empty Weight and Speed

Candidate estimating relationships are D7, D16, D17, and D21. All but equation D7 are eliminated for reasons of exponent magnitude. Unfortunately, equation D7 shows a tendency to underestimate the most recent aircraft in the sample.

$$\text{D7} \quad DS = .00417\ EW^{.818}\ SP^{1.23}$$
$$(.000)(.001)$$

| $R^2$ | SEE | F | N | RP |
|---|---|---|---|---|
| .52 | .80 | 16 | 32 | CUR:UNDER |

## Empty Weight and Climb

Candidate estimating relationships are D9, D18, D19, and D22. All but equation D9 are eliminated for reasons of exponent magnitude. Unfortunately, equation D9 shows a tendency to underestimate the most recent aircraft in the sample.

$$\text{D9} \quad DS = .0331\ EW^{.894}\ CLIMB^{.553}$$
$$(.000)\ (.002)$$

| $R^2$ | SEE | F | N | RP |
|---|---|---|---|---|
| .49 | .83 | 14 | 32 | CUR:UNDER |

## Single Best Estimating Relationship

Based on a summary examination of all 22 development support equations, the list of candidate estimating relationships was narrowed to include the four equations discussed above plus D5 and D8. All show a tendency to underestimate the most recent sample aircraft. Equation D8 is selected because it has the lowest standard error of estimate:

$$\text{D8} \quad DS = 10.5\ EW^{.794}\ SPCLS^{1.08}$$
$$(.000)\ (.000)$$

| $R^2$ | SEE | F | N | RP |
|---|---|---|---|---|
| .54 | .78 | 17 | 32 | CUR:UNDER |

## SUMMARY

Each of the representative CERs shows a tendency to underestimate development support costs for the most recent aircraft in the sample. Furthermore, the standard errors of estimate for the representative CERs are all much larger than the goal of 0.18. Finally, the exponents of the construction/program variables found to be significant at the 5 percent level (number of black boxes, ratio of avionics weight to airframe unit weight, and the program type designator) produce results that are not credible.

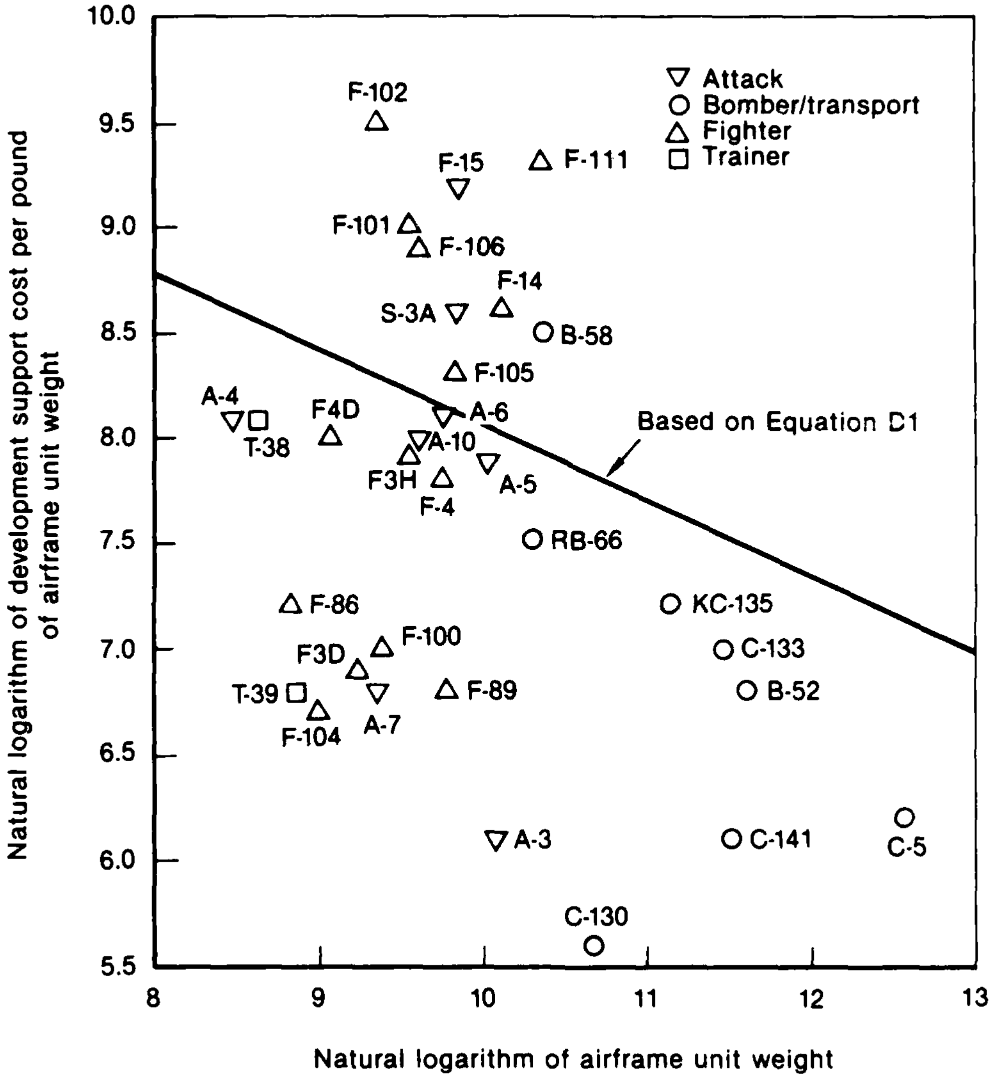



Fig. 7—Development support cost per pound as a function of airframe unit weight

Table 9

DEVELOPMENT SUPPORT COST ESTIMATING RELATIONSHIPS

| Eq. No. | Equation | Statistics | | | | Relative Deviations (%) | | | | | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $R^2$ | SEE | F | N | A-10 | C-141 | F-14 | F-15 | Abs Avg | |
| | SIZE | | | | | | | | | | |
| D1 | $DS = 125\ AUW^{.634}$ (.001) | .28 | .96 | 12 | 32 | -28 | -299 | +42 | +62 | 108 | RP:CUR:UNDER |
| D2 | $DS = 46.1\ EW^{.706}$ (.000) | .31 | .94 | 14 | 32 | -15 | -308 | +44 | +62 | 107 | RP:CUR:UNDER |
| D3 | $DS = 1230\ WTAREA^{.518}$ (.012) | .17 | 1.01 | 6 | 29 | -62 | -264 | +42 | +55 | 106 | RP:CUR:UNDER 10:C-130, F-104 |
| | SIZE/PERFORMANCE | | | | | | | | | | |
| D4 | $DS = .00761\ AUW^{.761}\ SP^{1.28}$ (.000) (.001) | .50 | .82 | 15 | 32 | +47 | -188 | -22 | +23 | 70 | RP:CUR:UNDER 10:F-104 |
| D5 | $DS = 28.0\ AUW^{.727}\ SPCLS^{1.09}$ (.000) (.000) | .51 | .81 | 15 | 32 | +30 | -162 | -10 | +30 | 58 | RP:CUR:UNDER 10:F-104 |
| D6 | $DS = .0780\ AUW^{.829}\ CLIMB^{.567}$ (.000) (.002) | .46 | .85 | 12 | 32 | +34 | -268 | -16 | +16 | 84 | RP:CUR:UNDER 10:F-104 |
| D7 | $DS = .00417\ EW^{.818}\ SP^{1.23}$ (.000) (.001) | .52 | .80 | 16 | 32 | +51 | -191 | -15 | +24 | 70 | RP:CUR:UNDER 10:F-104 |

Table 9 (continued)

| Eq. No. | Equation | Statistics $R^2$ | SEE | F | N | Relative Deviations (%) A-10 | C-141 | F-14 | F-15 | Abs Avg | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| D8 | $DS = 10.5\ EW^{.794}_{(.000)}\ SPCLS^{1.08}_{(.000)}$ | .54 | .78 | 17 | 32 | +37 | -166 | -5 | +30 | 60 | RP:CUR:UNDER<br>IO:F-104 |
| D9 | $DS = .0331\ EW^{.894}_{(.000)}\ CLIMB^{.553}_{(.002)}$ | .49 | .83 | 14 | 32 | +41 | -269 | -9 | +16 | 84 | RP:CUR:UNDER<br>IO:F-104 |
| D10 | $DS = .0176\ WTAREA^{.779}_{(.000)}\ SP^{1.36}_{(.001)}$ | .43 | .86 | 10 | 29 | +39 | -195 | -21 | +9 | 66 | RP:CUR:UNDER<br>IO:F-104 |
| D11 | $DS = 138\ WTAREA^{.711}_{(.000)}\ SPCLS^{1.15}_{(.001)}$ | .44 | .85 | 10 | 29 | +17 | -160 | -8 | +18 | 51 | RP:CUR:UNDER<br>IO:F-104 |
| D12 | $DS = .361\ WTAREA^{.816}_{(.001)}\ CLIMB^{.597}_{(.005)}$ | .36 | .90 | 7 | 29 | +20 | -274 | -14 | -2 | 78 | RP:CUR:UNDER<br>IO:F-104 |
| | SIZE/PERFORMANCE/CONSTRUCTION | | | | | | | | | | |
| D13 | $DS = .0508\ AUW^{.936}_{(.000)}\ SP^{.954}_{(.011)}\ AVAUW^{.586}_{(.019)}$ | .52 | .81 | 8 | 27 | +57 | -115 | -32 | +32 | 59 | RP:CUR:UNDER<br>EXP MAG:AVAUW |
| D14 | $DS = .0525\ AUW^{.439}_{(.023)}\ SP^{1.17}_{(.001)}\ BLBOX^{.770}_{(.017)}$ | .58 | .78 | 13 | 31 | +34 | -197 | -50 | -19 | 75 | MCOL:r(AUW) > .7<br>EXP MAG:BLBOX |

Table 9 (continued)

| Eq. No. | Equation | Statistics $R^2$ | SEE | F | N | Relative Deviations (%) A-10 | C-141 | F-14 | F-15 | Abs Avg | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| D15 | $DS = .136\ AUW^{1.03}\ CLIMB^{.478}\ AVAUW^{.682}$ (.000) (.008) (.007) | .53 | .80 | 8 | 27 | +57 | -134 | -39 | +22 | 63 | RP:CUR:UNDER EXP MAG:AVAUW |
| D16 | $DS = .0196\ EW^{.990}\ SP^{.942}\ AVAUW^{.542}$ (.000) (.011) (.024) | .52 | .81 | 8 | 27 | +60 | -122 | -24 | +31 | 59 | RP:CUR:UNDER EXP MAG:AVAUW |
| D17 | $DS = .0291\ EW^{.499}\ SP^{1.15}\ BLBOX^{.732}$ (.014) (.001) (.019) | .59 | .76 | 13 | 31 | +38 | -202 | -43 | -16 | 75 | EXP MAG:AVAUW |
| D18 | $DS = .244\ EW^{.831}\ CLIMB^{.333}\ WGTYPE^{.998}$ (.000) (.049) (.018) | .56 | .78 | 12 | 32 | +64 | -267 | -56 | +43 | 108 | EXP MAG:WGTYPE |
| D19 | $DS = .0564\ EW^{1.08}\ CLIMB^{.461}\ AVAUW^{.630}$ (.000) (.010) (.010) | .53 | .80 | 8 | 27 | +60 | -142 | -28 | +22 | 63 | RP:CUR:UNDER EXP MAG:AVAUW |
| | <u>SIZE/PERFORMANCE/PROGRAM</u> | | | | | | | | | | |
| D20 | $DS = 4.46\ AUW^{.528}\ SP^{.711}\ PRGDV^{-1.40}$ (.001) (.029) (.002) | .63 | .72 | 16 | 32 | +57 | -244 | -15 | +20 | 84 | EXP MAG:PRGDV RP:CUR:UNDER |
| D21 | $DS = 2.29\ EW^{.584}\ SP^{.692}\ PRGDV^{-1.38}$ (.001) (.027) (.002) | .65 | .70 | 17 | 32 | +59 | -250 | -10 | +21 | 85 | EXP MAG:PRGDV RP:CUR:UNDER |
| D22 | $DS = 10.3\ EW^{.609}\ CLIMB^{.296}\ PRGDV^{-1.48}$ (.001) (.044) (.001) | .64 | .71 | 17 | 32 | +56 | -302 | -8 +17 | | 96 | EXP MAG:PRGDV RP:CUR:UNDER |

# IX. FLIGHT TEST

Flight test cost per aircraft is plotted as a function of the quantity of flight test aircraft in Fig. 8. Estimating relationships in which all equation variables are significant at the 5 percent level are provided in Table 10.

## GENERAL OBSERVATIONS

1. In general, the flight test estimating relationships have relatively high standard errors of estimate compared to the goal of 0.18. On the other hand, with the exception of those equations incorporating the speed class designator, they are relatively free of residual patterns.

2. The magnitude of the test aircraft variable is less than one only when a performance variable is included in the equation. Additionally, the magnitude of the test aircraft exponent varies considerably depending on what other variables are included in the equation.

3. The exponents associated with three of the construction variables seem fairly large although we are not able to say they are not credible. Equations F14, F19, F23, and F28 indicate that a carrier-capable aircraft will incur flight test costs 60 percent to 70 percent greater than those of a land-based aircraft. Equations F15, F20, F24, and F29 indicate that a variable-sweep aircraft will incur flight test costs 80 percent to 120 percent greater than a swept-wing aircraft. And finally, equations F16, F21, F25, and F30 indicate that a 30 percent increase in the EWAUW value will result in a 20 percent to 35 percent increase in flight test costs.

4. The equations containing the black box variable (F18, F22, and F27) all do very poorly with respect to F-15 flight test costs.

## REPRESENTATIVE CERS

### Airframe Unit Weight and Speed

Candidate estimating relationships are F5, F14, F15, F16, F17, and F18. Equations F14, F15, and F16 are ruled out because of previously discussed reservations concerning the magnitude of the construction variable exponents. Equation F18 is ruled out because of its poor performance with respect to the F-15. Of the two remaining estimating relationships, F5 is preferred to F17 because there is little difference statistically and F5 contains fewer variables:

$$\text{F5 FT} = .00617\ \underset{(.000)}{\text{AUW}^{.584}}\ \underset{(.000)}{\text{SP}^{1.27}}\ \underset{(.002)}{\text{TESTAC}^{.805}}$$

| $R^2$ | SEE | F | N | RP |
|---|---|---|---|---|
| .71 | .60 | 23 | 32 | None |

### Airframe Unit Weight and Climb

Candidate estimating relationships are F7, F19, F20, F21, and F22. Equations F19, F20, and F21 are ruled out because of previously discussed reservations concerning the magnitude of the construction variable exponents. Equation F22 is ruled out because of its poor performance with respect to the F-15. This leaves equation F7 as the only survivor:

$$\text{F7 FT} = .0859\ \underset{(.000)}{\text{AUW}^{.641}}\ \underset{(.002)}{\text{CLIMB}^{.512}}\ \underset{(.001)}{\text{TESTAC}^{.916}}$$

| $R^2$ | SEE | F | N | RP |
|---|---|---|---|---|
| .65 | .66 | 18 | 32 | None |

### Empty Weight and Speed

Candidate estimating relationships are F8, F23, F24, F25, F26, and F27. Equations F23, F24, and F25 are ruled out because of previously discussed reservations concerning the magnitude of the construction variable exponents. Equation F27 is ruled out because of its poor performance with respect to the F-15. Of the two remaining estimating relationships, F8 is preferred to F26 because there is little difference statistically and F8 contains fewer variables:

$$F8\ FT = .00293\ \underset{(.000)}{EW^{.644}}\ \underset{(.000)}{SP^{1.27}}\ \underset{(.002)}{TESTAC^{.767}}$$

| $R^2$ | SEE | F | N | RP |
|---|---|---|---|---|
| .74 | .58 | 26 | 32 | CUR:UNDER |

### Empty Weight and Climb

Candidate estimating relationships are F10, F28, F29, F30, and F31. Equations F28, F29, and F30 are ruled out because of previously discussed reservations concerning the magnitude of the construction variable exponents. Of the two remaining equations, F31 is preferred to F10 because of its lower standard error of estimate:

$$F31\ FT = .0332\ \underset{(.000)}{EW^{.877}}\ \underset{(.000)}{CLIMB^{.571}}\ \underset{(.006)}{AVAUW^{.488}}\ \underset{(.049)}{TESTAC^{.491}}$$

| $R^2$ | SEE | F | N | RP |
|---|---|---|---|---|
| .71 | .56 | 13 | 27 | None |

### Single Best Estimating Relationship

Based on a summary examination of all 31 flight test equations, the list of candidate estimating relationships has been narrowed to the four equations discussed above. Of the four possibilities, F5, F8, and F31 are all on about the same level. Equation F8 is arbitrarily selected:

$$F8\ FT = .00293\ \underset{(.000)}{EW^{.644}}\ \underset{(.000)}{SP^{1.27}}\ \underset{(.002)}{TESTAC^{.767}}$$

| $R^2$ | SEE | F | N | RP |
|---|---|---|---|---|
| .74 | .58 | 26 | 32 | None |

## SUMMARY

The standard errors of estimate for the representative CERs are all considerably greater than the goal of 0.18. Additionally, the exponents of three of the five construction variables determined to be significant at the 5 percent level (carrier capable designator, wing type designator, and the ratio of empty weight minus airframe unit weight to airframe unit weight) produce results that seem extreme. The other two construction variables determined to be significant at the 5 percent level provided relatively modest reductions in the standard error of estimate for the equations into which they were incorporated.

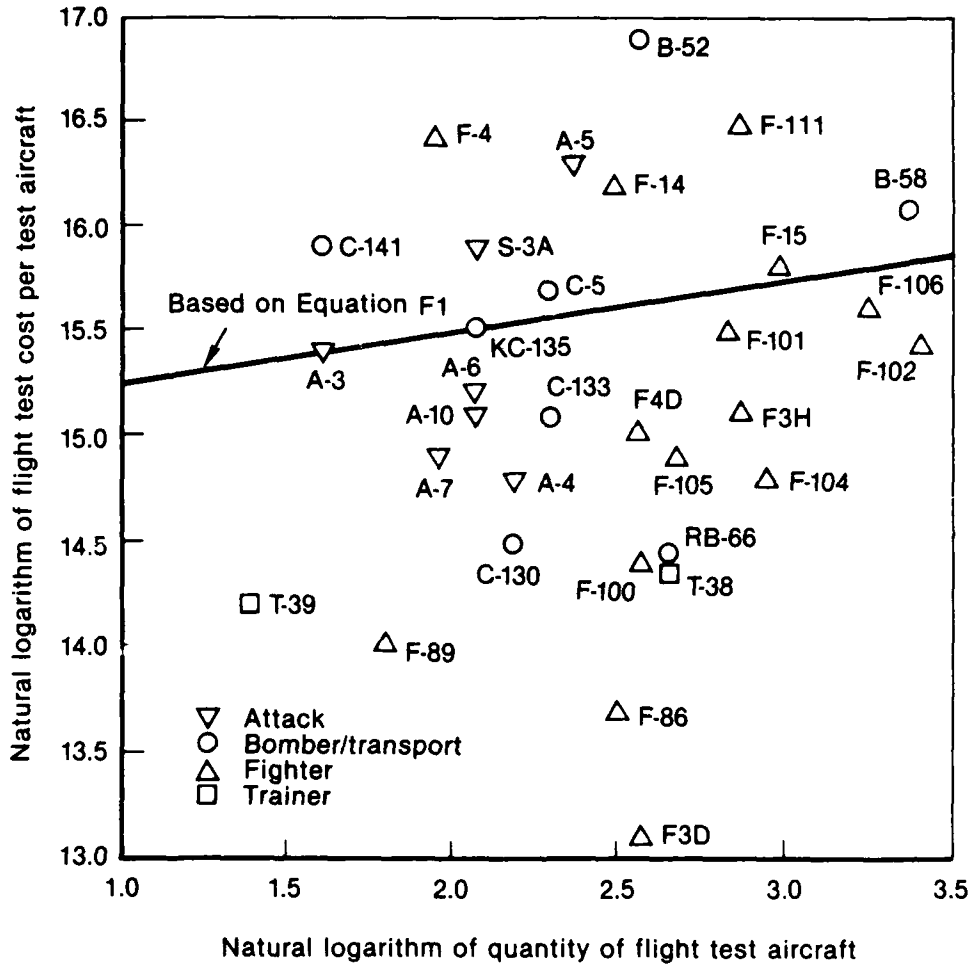



Fig. 8—Flight test cost per test aircraft as a function of the quantity of flight test aircraft

Table 10

FLIGHT TEST COST ESTIMATING RELATIONSHIPS

| Eq. No. | Equation | Statistics $R^2$ | SEE | F | N | Relative Deviations (%) A-10 | C-141 | F-14 | F-15 | Abs Avg | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | TESTAC | | | | | | | | | | |
| F1 | $FT = 3320\ TESTAC^{1.24}$ <br> (.000) | .35 | .88 | 16 | 32 | -52 | +40 | +45 | +5 | 36 | EXP MAG:TESTAC <br> RP:CUR:UNDER <br> IO:F3D |
| | SIZE/TESTAC | | | | | | | | | | |
| F2 | $FT = 16.7\ AUW^{.495}\ TESTAC^{1.35}$ <br> (.001) (.000) | .53 | .75 | 17 | 32 | -13 | -11 | +44 | +16 | 21 | EXP MAG:TESTAC <br> RP:CUR:UNDER <br> IO:C-5 |
| F3 | $FT = 7.85\ EW^{.556}\ TESTAC^{1.32}$ <br> (.000) (.000) | .56 | .73 | 19 | 32 | -5 | -17 | +45 | +17 | 21 | EXP MAG:TESTAC <br> RP:CUR:UNDER <br> IO:C-5 |
| F3 | $FT = 129\ WTAREA^{.415}\ TESTAC^{1.21}$ <br> (.013) (.000) | .38 | .79 | 8 | 29 | -42 | -18 | +44 | +12 | 29 | EXP MAG:TESTAC <br> RP:CUR:UNDER |
| | SIZE/PERFORMANCE/TESTAC | | | | | | | | | | |
| F5 | $FT = .00617\ AUW^{.584}\ SP^{1.27}\ TESTAC^{.805}$ <br> (.000) (.000) (.002) | .71 | .60 | 23 | 32 | +40 | -23 | -19 | -30 | 28 | |
| F6 | $FT = 25.8\ AUW^{.540}\ SPCLS^{.978}\ TESTAC^{.798}$ <br> (.000) (.001) (.004) | .67 | .64 | 19 | 32 | +15 | -19 | -2 | -13 | 12 | RP:CUR:UNDER |
| F7 | $FT = .0859\ AUW^{.641}\ CLIMB^{.512}\ TESTAC^{.916}$ <br> (.000) (.002) (.001) | .65 | .66 | 18 | 32 | +25 | -45 | -6 | -40 | 29 | |
| F8 | $FT = .00293\ EW^{.644}\ SP^{1.27}\ TESTAC^{.767}$ <br> (.000) (.000) (.002) | .74 | .58 | 26 | 32 | +44 | -28 | -15 | -28 | 29 | RP:CUR:UNDER |
| F9 | $FT = 11.3\ EW^{.610}\ SPCLS^{1.00}\ TESTAC^{.750}$ <br> (.000) (.001) (.004) | .70 | .61 | 22 | 32 | +22 | -26 | 0 | -12 | 15 | RP:CUR:UNDER |

Table 10 (continued)

| Eq. No. | Equation | Statistics $R^2$ | SEE | F | N | Relative Deviations (%) A-10 | C-141 | F-14 | F-15 | Abs Avg | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| F10 | $FT = .0331\ EW^{.711}\ CLIMB^{.523}\ TESTAC^{.864}$<br>(.000) (.001) (.001) | .68 | .63 | 20 | 32 | +32 | -54 | -4 | -39 | 32 | RP:CUR:UNDER |
| F11 | $FT = .00744\ WTAREA^{.612}\ SP^{1.46}\ TESTAC^{.599}$<br>(.000) (.000) (.020) | .67 | .59 | 17 | 29 | +34 | -44 | -25 | -41 | 36 | |
| F12 | $FT = 156\ WTAREA^{.517}\ SPCLS^{1.12}\ TESTAC^{.571}$<br>(.001) (.000) (.039) | .61 | .64 | 13 | 29 | -1 | -35 | -8 | -21 | 16 | RP:CUR:UNDER<br>IO:B-52 |
| F13 | $FT = .140\ WTAREA^{.663}\ CLIMB^{.629}\ TESTAC^{.723}$<br>(.000) (.001) (.012) | .59 | .66 | 12 | 29 | +16 | -69 | -16 | -66 | 42 | |
| | <u>SIZE/PERFORMANCE/CONSTRUCTION/TESTAC</u> | | | | | | | | | | |
| F14 | $FT = .00318\ AUW^{.652}\ SP^{1.17}\ CARRDV^{.668}\ TESTAC^{.979}$<br>(.000) (.000) (.031) (.000) | .75 | .58 | 20 | 32 | +51 | -2 | -53 | -12 | 30 | IO:F3D<br>EXP MAG:CARRDV |
| F15 | $FT = .111\ AUW^{.558}\ SP^{.788}\ WGTYPE^{.900}\ TESTAC^{.746}$<br>(.000) (.016) (.012) (.002) | .76 | .56 | 21 | 32 | +57 | -41 | -57 | +10 | 41 | MCOL:r(SP) > .7<br>EXP MAG:WGTYPE |
| F16 | $FT = .00563\ AUW^{.788}\ SP^{1.16}\ EWAUW^{1.00}\ TESTAC^{.636}$<br>(.000) (.000) (.002) (.005) | .79 | .53 | 25 | 32 | +53 | -38 | +2 | -24 | 29 | EXP MAG:EWAUW |
| F17 | $FT = .0196\ AUW^{.696}\ SP^{1.17}\ AVAUW^{.386}\ TESTAC^{.547}$<br>(.000) (.000) (.029) (.037) | .68 | .58 | 12 | 27 | +45 | -24 | -38 | -16 | 31 | |
| F18 | $FT = .0425\ AUW^{.331}\ SP^{1.06}\ BLBOX^{.631}\ TESTAC^{.946}$<br>(.017) (.001) (.008) (.000) | .78 | .55 | 23 | 31 | +26 | -21 | -33 | -89 | 42 | MCOL:r(AUW) > .7 |
| F19 | $FT = .0254\ AUW^{.722}\ CLIMB^{.485}\ CARRDV^{.798}\ TESTAC^{1.10}$<br>(.000) (.002) (.019) (.000) | .70 | .62 | 16 | 32 | +43 | -16 | -48 | -18 | 31 | IO:F3D<br>EXP MAG:TESTAC<br>EXP MAG:CARRDV |
| F20 | $FT = .540\ AUW^{.596}\ CLIMB^{.321}\ WGTYPE^{1.13}\ TESTAC^{.745}$<br>(.000) (.023) (.001) (.002) | .75 | .57 | 21 | 32 | +58 | -64 | -69 | +10 | 50 | EXP MAG:WGTYPE |

Table 10 (continued)

| Eq. No. | Equation | Statistics $R^2$ | SEE | F | N | Relative Deviations (%) A-10 | C-141 | F-14 | F-15 | Abs Avg | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| F21 | $FT = .0411\ \underset{(.000)}{AUW^{.878}}\ \underset{(.001)}{CLIMB^{.496}}\ \underset{(.001)}{EWAUW^{1.14}}\ \underset{(.005)}{TESTAC^{.682}}$ | .76 | .57 | 21 | 32 | +46 | -67 | +9 | -36 | 40 | EXP MAG:EWAUW |
| F22 | $FT = .479\ \underset{(.026)}{AUW^{.334}}\ \underset{(.006)}{CLIMB^{.420}}\ \underset{(.005)}{BLBOX^{.734}}\ \underset{(.000)}{TESTAC^{1.05}}$ | .74 | .59 | 18 | 31 | +9 | -38 | -25 | -114 | 46 | MCOL:r(AUW > .7<br>EXP MAG:TESTAC |
| F23 | $FT = .00168\ \underset{(.000)}{EW^{.703}}\ \underset{(.000)}{SP^{1.17}}\ \underset{(.033)}{CARRDV^{.623}}\ \underset{(.000)}{TESTAC^{.926}}$ | .77 | .55 | 22 | 32 | +54 | -8 | -44 | -11 | 29 | IO:F3D<br>EXP MAG:CARRDV |
| F24 | $FT = .0477\ \underset{(.000)}{EW^{.611}}\ \underset{(.011)}{SP^{.819}}\ \underset{(.015)}{WGTYPE^{.831}}\ \underset{(.002)}{TESTAC^{.714}}$ | .78 | .54 | 24 | 32 | +59 | -45 | -48 | +9 | 40 | MCOL:r(SP) > .7<br>EXP MAG:WGTYPE |
| F25 | $FT = .00361\ \underset{(.000)}{EW^{.780}}\ \underset{(.000)}{SP^{1.16}}\ \underset{(.008)}{EWAUW^{.770}}\ \underset{(.005)}{TESTAC^{.629}}$ | .79 | .53 | 25 | 32 | +53 | -37 | +2 | -23 | 29 | EXP MAG:EWAUW |
| F26 | $FT = .00703\ \underset{(.000)}{EW^{.766}}\ \underset{(.000)}{SP^{1.18}}\ \underset{(.026)}{AVAUW^{.371}}\ \underset{(.033)}{TESTAC^{.535}}$ | .71 | .56 | 14 | 27 | +50 | -29 | -32 | -16 | 32 | |
| F27 | $FT = .0194\ \underset{(.006)}{EW^{.405}}\ \underset{(.000)}{SP^{1.08}}\ \underset{(.012)}{BLBOX^{.569}}\ \underset{(.000)}{TESTAC^{.913}}$ | .79 | .53 | 25 | 31 | +31 | -26 | -29 | -80 | 42 | |
| F28 | $FT = .0116\ \underset{(.000)}{EW^{.781}}\ \underset{(.001)}{CLIMB^{.494}}\ \underset{(.020)}{CARRV^{.745}}\ \underset{(.000)}{TESTAC^{1.03}}$ | .73 | .59 | 18 | 32 | +47 | -24 | -40 | -18 | 32 | IO:F3D<br>EXP MAG:TESTAC<br>EXP MAG:CARRDV |
| F29 | $FT = .229\ \underset{(.000)}{EW^{.653}}\ \underset{(.015)}{CLIMB^{.338}}\ \underset{(.001)}{WGTYPE^{1.06}}\ \underset{(.002)}{TESTAC^{.708}}$ | .77 | .54 | 23 | 32 | +60 | -70 | -60 | +9 | 50 | EXP MAG:WGTYPE |
| F30 | $FT = .0269\ \underset{(.000)}{EW^{.867}}\ \underset{(.001)}{CLIMB^{.495}}\ \underset{(.006)}{EWAUW^{.882}}\ \underset{(.005)}{TESTAC^{.678}}$ | .75 | .57 | 21 | 32 | +46 | -64 | +10 | -35 | 39 | EXP MAG:EWAUW |
| F31 | $FT = .0332\ \underset{(.000)}{EW^{.877}}\ \underset{(.000)}{CLIMB^{.571}}\ \underset{(.006)}{AVAUW^{.488}}\ \underset{(.049)}{TESTAC^{.491}}$ | .71 | .56 | 13 | 27 | +48 | -48 | -37 | -31 | 41 | |

# X. QUALITY CONTROL

Quality control hours per pound are plotted as a function of airframe unit weight in Fig. 9. Estimating relationships in which all equation variables are significant at the 5 percent level are provided in Table 11.

## GENERAL OBSERVATIONS

1. All 18 equations listed in Table 10 show a tendency to underestimate the quality control hours for the most recent aircraft in the sample.

2. The standard errors of estimate of those equations incorporating construction/program variables (Q13 through Q18) are only slightly lower than the standard errors of estimate of analogous equations not incorporating construction/program variables.

3. The magnitude of the exponents associated with the contractor experience designator seems somewhat large. Equations Q15 through Q18 indicate that a contractor without relevant experience will incur 40 percent to 50 percent more quality control hours than a contractor with relevant experience.

## REPRESENTATIVE CERS

Previous RAND airframe models have estimated quality control hours as a percentage of manufacturing labor hours. Because all of the equations listed in Table 11 exhibit a tendency to underestimate the quality control hours of the most recent aircraft in the sample, the simpler factor approach will again be used. The recommended factors, based on the data shown in Table 12, are as follows:

| Quality Control Hours as % of Manufacturing Labor Hours | Mission Type |
|---|---|
| 8.5 | Cargo |
| 12.5 | Non-cargo |

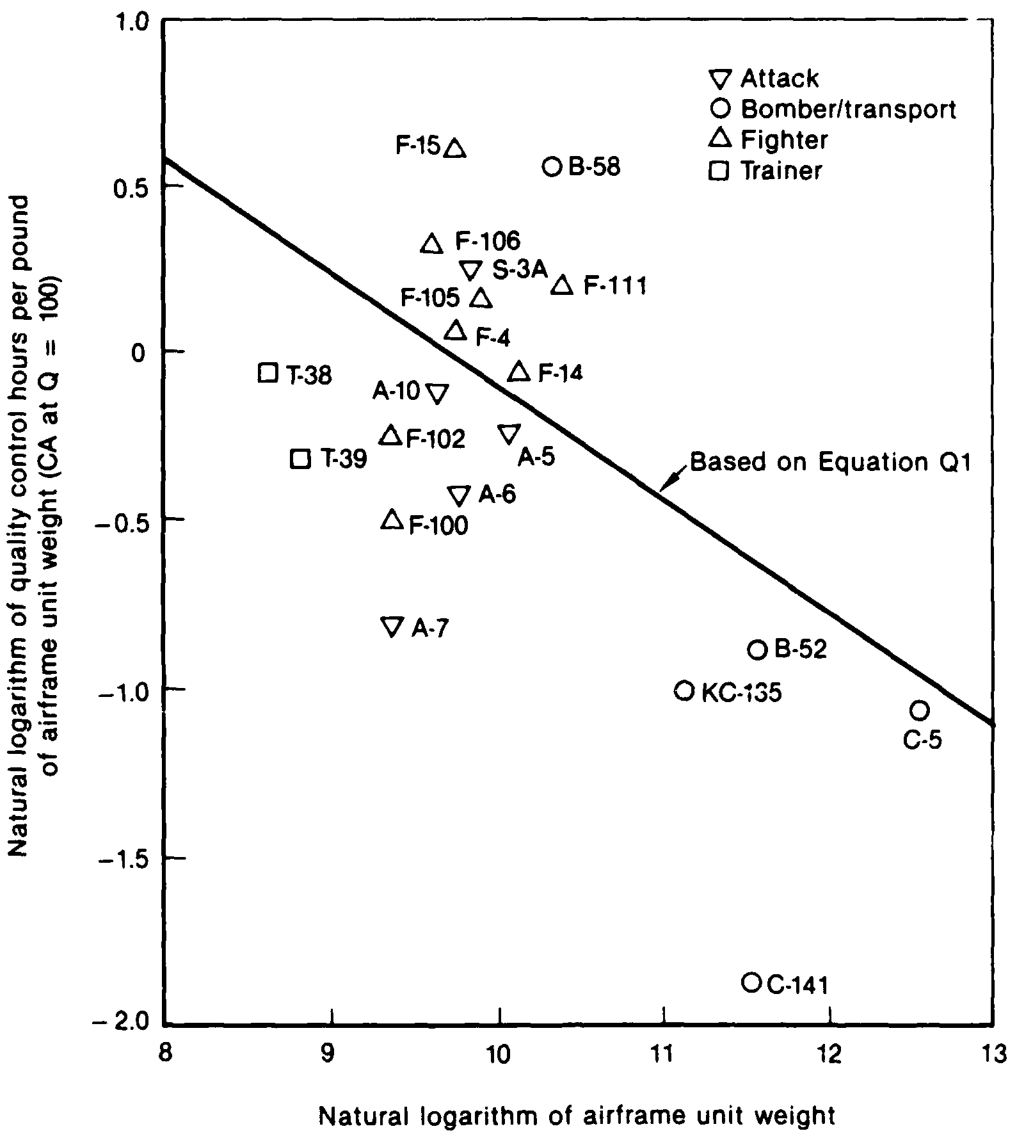



Fig. 9—Quality control hours per pound as a function of airframe unit weight

Table 11

QUALITY CONTROL HOUR ESTIMATING RELATIONSHIPS

| Eq. No. | Equation | Statistics | | | | Relative Deviations (%) | | | | | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $R^2$ | SEE | F | N | A-10 | C-141 | F-14 | F-15 | Abs Avg | |
| | SIZE | | | | | | | | | | |
| Q1 | $QC_{100} = 2.82\ AUW^{.657}$ (.000) | .60 | .53 | 27 | 20 | -22 | -245 | +10 | +48 | 81 | RP:CUR:UNDER IO:A-7,C-141 |
| Q2 | $QC_{100} = 1.57\ EW^{.689}$ (.000) | .63 | .51 | 31 | 20 | -13 | -238 | +13 | +47 | 78 | RP:CUR:UNDER IO:A-7,C-141 |
| Q3 | $QC_{100} = 27.2\ WTAREA^{.550}$ (.001) | .43 | .57 | 12 | 18 | -56 | -222 | +10 | +38 | 82 | RP:CUR:UNDER IO:A-7,C-5,C-141 |
| | SIZE/PERFORMANCE | | | | | | | | | | |
| Q4 | $QC_{100} = .00962\ AUW^{.713}\ SP^{.765}$ (.000) (.002) | .76 | .43 | 27 | 20 | +32 | -158 | -32 | +25 | 62 | RP:CUR:UNDER IO:C-141,S-3 |
| Q5 | $QC_{100} = .650\ AUW^{.759}\ SPCLS^{.687}$ (.000) (.001) | .78 | .41 | 30 | 20 | +25 | -161 | -25 | +30 | 60 | RP:CUR:UNDER IO:C-141,S-3 |
| Q6 | $QC_{100} = .0599\ AUW^{.758}\ CLIMB^{.293}$ (.000) (.022) | .69 | .49 | 19 | 20 | +16 | -220 | -25 | +24 | 71 | RP:CUR:UNDER IO:C-141 |
| Q7 | $QC_{100} = .00854\ EW^{.732}\ SP^{.713}$ (.000) (.003) | .77 | .42 | 28 | 20 | +34 | -154 | -25 | +24 | 59 | RP:CUR:UNDER IO:C-141,S-3 |
| Q8 | $QC_{100} = .421\ EW^{.777}\ SPCLS^{.642}$ (.000) (.001) | .79 | .40 | 31 | 20 | +28 | -156 | -19 | +29 | 58 | RP:CUR:UNDER IO:C-141,S-3 |
| Q9 | $QC_{100} = .0430\ EW^{.780}\ CLIMB^{.274}$ (.000) (.024) | .71 | .47 | 21 | 20 | +21 | -211 | -19 | +24 | 69 | RP:CUR:UNDER IO:C-141 |

Table 11 (continued)

| Eq. No. | Equation | $R^2$ | SEE | F | N | A-10 | C-141 | F-14 | F-15 | Abs Avg | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Statistics | | | | Relative Deviations (%) | | | | | |
| Q10 | $QC_{100} = .0220\ \underset{(.000)}{WTAREA^{.714}}\ \underset{(.004)}{SP^{.859}}$ | .66 | .46 | 14 | 18 | +23 | -157 | -31 | +12 | 56 | RP:CUR:UNDER IO:C-5,C-141,S-3 |
| Q11 | $QC_{100} = 2.95\ \underset{(.000)}{WTAREA^{.759}}\ \underset{(.002)}{SPCLS^{.767}}$ | .68 | .45 | 16 | 18 | +13 | -159 | -23 | +18 | 53 | RP:CUR:UNDER IO:C-5,C-141,S-3 |
| Q12 | $QC_{100} = .359\ \underset{(.000)}{WTAREA^{.714}}\ \underset{(.051)}{CLIMB^{.308}}$ | .53 | .54 | 8 | 18 | -3 | -216 | -23 | +10 | 63 | RP:CUR:UNDER IO:C-141,S-3 |
| | SIZE/PERFORMANCE/CONSTRUCTION | | | | | | | | | | |
| Q13 | $QC_{100} = .0105\ \underset{(.000)}{AUW^{.577}}\ \underset{(.001)}{SP^{.775}}\ \underset{(.038)}{BLBOX^{.435}}$ | .80 | .40 | 22 | 20 | +32 | -159 | -47 | +7 | 61 | RP:CUR:UNDER IO:C-141,S-3 |
| Q14 | $QC_{100} = .00962\ \underset{(.000)}{EW^{.598}}\ \underset{(.002)}{SP^{.732}}\ \underset{(.043)}{BLBOX^{.416}}$ | .81 | .39 | 22 | 20 | +34 | -156 | -40 | +7 | 59 | RP:CUR:UNDER IO:C-5,C-141,S-3 |
| | SIZE/PERFORMANCE/PROGRAM | | | | | | | | | | |
| Q15 | $QC_{100} = .00344\ \underset{(.000)}{AUW^{.768}}\ \underset{(.001)}{SP^{.814}}\ \underset{(.042)}{EXPDV^{.511}}$ | .80 | .40 | 21 | 20 | +21 | -136 | -17 | +35 | 52 | RP:CUR:UNDER IO:C-141 |
| Q16 | $QC_{100} = .0144\ \underset{(.000)}{AUW^{.834}}\ \underset{(.009)}{CLIMB^{.344}}\ \underset{(.047)}{EXPDV^{.574}}$ | .74 | .46 | 15 | 20 | +4 | -191 | -12 | +33 | 60 | RP:CUR:UNDER IO:C-141 |
| Q17 | $QC_{100} = .00332\ \underset{(.000)}{EW^{.783}}\ \underset{(.001)}{SP^{.754}}\ \underset{(.048)}{EXPDV^{.482}}$ | .81 | .40 | 22 | 20 | +24 | -132 | -12 | +34 | 50 | RP:CUR:UNDER IO:C-141 |
| Q18 | $QC_{100} = .0116\ \underset{(.000)}{EW^{.850}}\ \underset{(.011)}{CLIMB^{.319}}\ \underset{(.050)}{EXPDV^{.542}}$ | .75 | .44 | 16 | 20 | +10 | -183 | -7 | +32 | 58 | RP:CUR:UNDER IO:C-141 |

Table 12

QUALITY CONTROL HOURS AS A PERCENTAGE OF MANUFACTURING LABOR HOURS (AT Q = 100)

| Aircraft | QC Percentage |
|---|---|
| A-5 | 9.8 |
| A-6 | 7.6 |
| A-7 | 10.4 |
| A-10 | 14.0 |
| B-52 | 9.5 |
| B-58 | 16.3 |
| C-5 | 9.7 |
| KC-135 | 10.3 |
| C-141 | 5.4 |
| F-4 | 7.6 |
| F-100 | 12.3 |
| F-102 | 6.9 |
| F-105 | 10.1 |
| F-106 | 17.2 |
| F-111 | 16.2 |
| F-14 | 11.6 |
| F-15 | 18.1 |
| T-38 | 14.4 |
| T-39 | 11.3 |
| S-3 | 17.1 |
| Average, all aircraft | 11.8 |
| Average, cargo aircraft | 8.5 |
| Average, non-cargo aircraft | 12.5 |

# XI. TOTAL PROGRAM COST

Total program cost per pound is plotted as a function of airframe unit weight in Fig. 10. Estimating relationships in which all equation variables are significant at the 5 percent level are provided in Table 13.

## GENERAL OBSERVATIONS

1. With the exception of the equations incorporating the black box variable (P16, P21, P34, P39, and P41), there is a definite tendency for the full-sample equations to underestimate the program costs of the most recent sample aircraft.

2. With the exception of the wing type designator, the construction variables that show up as significant at the 5 percent level relate to the equipment placed within the airframe structure (BLBOX, AVAUW, and EWAUW) rather than to the structure itself.

3. Of the four construction variables that were determined to be significant in the total sample (BLBOX, WGTYPE, AVAUW, and EWAUW), only two of them--AVAUW and EWAUW--were also found to be significant in a more limited analysis of 11 post-1960 aircraft. And even these two had difficulties--the magnitude of the EWAUW exponent in the post-1960 analysis increased by a factor of two to three over the full 32-aircraft sample, whereas the magnitude of the AVAUW exponent increased by roughly a factor of two.

4. The three program variables appearing in Table 13 have interesting implications. Based on minimum and maximum exponent values, the following results are obtained:

   a. A contractor without relevant experience would incur costs 25 percent to 40 percent greater than a contractor with relevant experience.

b. A prototype development approach would incur only 70 percent to 80 percent of the costs of a concurrent development approach.

c. An airframe using a new engine would incur costs approximately 20 percent higher than an airframe using an off-the-shelf engine.

Although we cannot say that such results are unreasonable, they do seem extreme and clearly highlight the difficulty associated with using simple yes/no variables--there is no middle ground. Furthermore, none of these three program variables that were determined to be significant at the 5 percent level in the 32-aircraft sample analysis was found to be significant in a more limited analysis of 11 post-1960 aircraft.

## REPRESENTATIVE CERS

### Airframe Unit Weight and Speed

Candidate estimating relationships are P4, P13, P14, P15, P16, P24, P30, P31, P32, P33, and P34. As stated in the general observations, each construction and program variable has difficulties that we feel preclude its incorporation in a recommended CER. Consequently, equation P4 is selected even though it has a tendency to underestimate the program costs of the most recent sample aircraft:

$$P4 \quad PROG_{100} = 3.56 \; AUW^{.779} \; SP^{.745}$$
$$(.000) \quad (.000)$$

| $R^2$ | SEE | F | N | RP |
|---|---|---|---|---|
| .85 | .31 | 85 | 32 | CUR:UNDER |

### Airframe Unit Weight and Climb

Candidate estimating relationships are P6, P17, P18, P19, P25, P35, P36, P37, P38, and P39. As stated in the general observations, each construction and program variable has difficulties that we feel preclude its incorporation in a recommended CER. Thus, equation P6 is selected as the AUW/CLIMB estimating relationship even though it has a tendency to underestimate the most recent sample aircraft:

$$P6 \quad PROG_{100} = 14.6\ AUW^{.817}_{(.000)}\ CLIMB^{.326}_{(.000)}$$

| $R^2$ | SEE | F | N | RP |
| --- | --- | --- | --- | --- |
| .82 | .35 | 66 | 32 | CUR:UNDER |

## Empty Weight and Speed

Candidate estimating relationships are P7, P20, P21, P26, P27, P40, and P41. As stated in the general observations, each construction and program variable has difficulties that we feel preclude its incorporation in a recommended CER. Consequently, equation P7 is arbitrarily selected even though it has a tendency to underestimate the program costs of the most recent sample aircraft:

$$P7 \quad PROG_{100} = 2.19\ EW^{.828}_{(.000)}\ SP^{.696}_{(.000)}$$

| $R^2$ | SEE | F | N | RP |
| --- | --- | --- | --- | --- |
| .88 | .29 | 102 | 32 | CUR:UNDER |

## Empty Weight and Climb

Candidate estimating relationships are P9, P22, P23, P28, P29, P42, and P43. As stated in the general observations, each construction and program variable has difficulties that we feel preclude its incorporation in a recommended CER. Thus, equation P9 is selected as the EW/CLIMB estimating relationship even though it has a tendency to underestimate the most recent sample aircraft:

$$P9 \quad PROG_{100} = 7.38\ EW^{.869}_{(.000)}\ CLIMB^{.308}_{(.000)}$$

| $R^2$ | SEE | F | N | RP |
| --- | --- | --- | --- | --- |
| .85 | .32 | 82 | 32 | CUR:UNDER |

## Single Best Estimating Relationship

Based on a summary examination of all 43 total program cost equations, the list of candidate estimating relationships has been narrowed to the four equations discussed above. Equation P7 has the lowest standard error of estimate of the four equations and is therefore selected:

$$\text{P7} \quad PROG_{100} = 2.19\ EW^{.828}\ SP^{.696}$$
$$\qquad\qquad\qquad\quad (.000)(.000)$$

| $R^2$ | SEE | F | N | RP |
|---|---|---|---|---|
| .88 | .29 | 102 | 32 | CUR:UNDER |

## SUMMARY

The standard errors of estimates for the representative CERs are all somewhat higher than the goal of 0.18. Furthermore, although several of the construction/program variables were found to be significant at the 5 percent level, each had difficulties that we felt precluded its incorporation in a recommended CER.

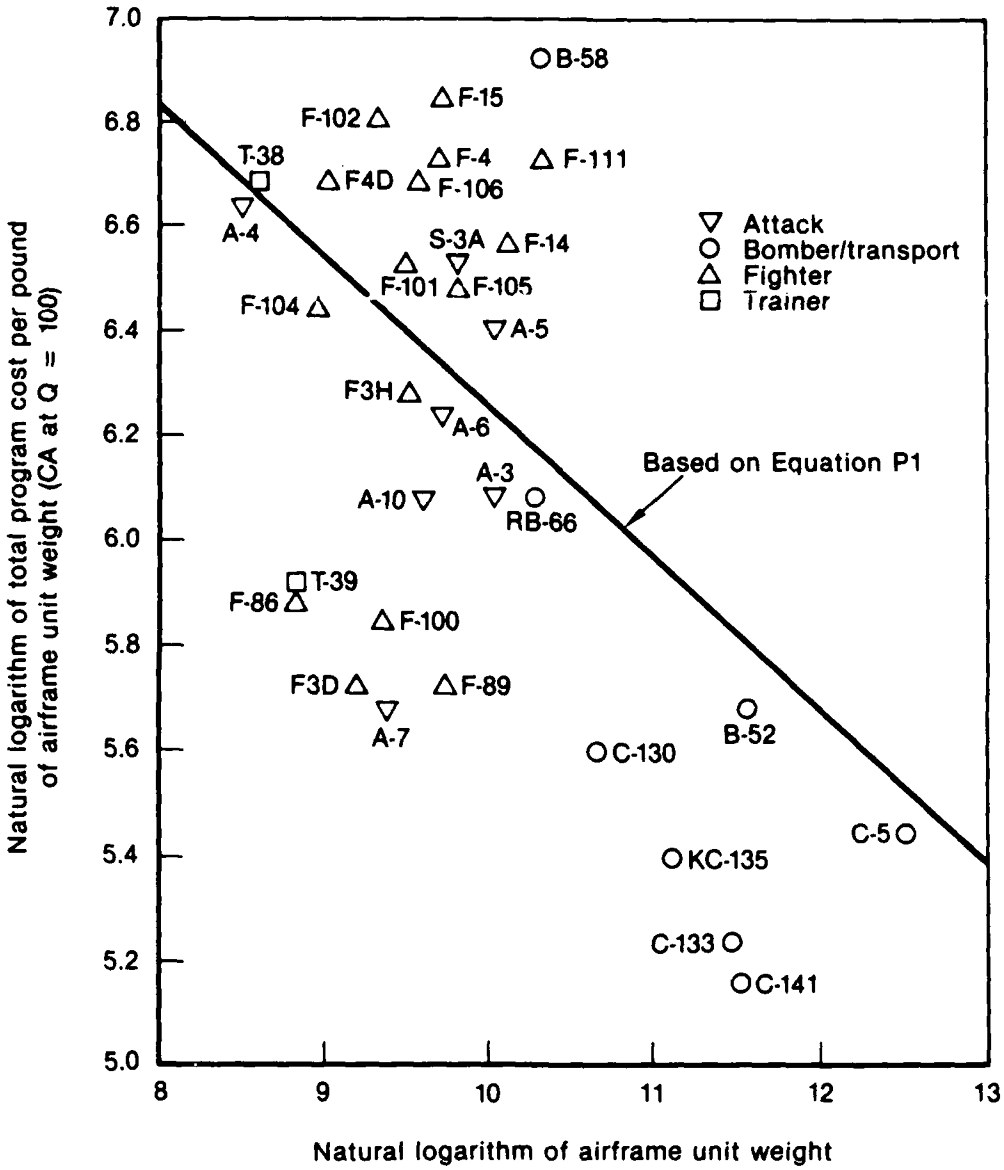



Fig. 10—Total program cost per pound as a function of airframe unit weight

Table 13

TOTAL PROGRAM COST ESTIMATING RELATIONSHIPS

| Eq. No. | Equation | Statistics | | | | Relative Deviations (%) | | | | | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $R^2$ | SEE | F | N | A-10 | C-141 | F-14 | F-15 | Abs Avg | |
| | SIZE | | | | | | | | | | |
| P1 | $PROG_{100} = 997\ AUW^{.705}$ (.000) | .70 | .44 | 71 | 32 | -32 | -85 | +30 | -41 | 47 | RP:CUR:UNDER 10:C-141 |
| P2 | $PROG_{100} = 408\ EW^{.764}$ (.000) | .74 | .41 | 86 | 32 | -20 | -86 | +32 | +40 | 44 | RP:CUR:UNDER 10:C-141 |
| P3 | $PROG_{100} = 5370\ WTAREA^{.673}$ (.000) | .60 | .49 | 40 | 29 | -56 | -80 | +34 | +35 | 51 | RP:CUR:UNDER 10:F-86 |
| | SIZE/PERFORMANCE | | | | | | | | | | |
| P4 | $PROG_{100} = 3.56\ AUW^{.779}\ SP^{.745}$ (.000) (.000) | .85 | .31 | 85 | 32 | +18 | -58 | -13 | +8 | 24 | RP:CUR:UNDER |
| P5 | $PROG_{100} = 444\ AUW^{.757}\ SPCLS^{.613}$ (.000) (.000) | .85 | .32 | 82 | 32 | +3 | -51 | -5 | +14 | 18 | RP:CUR:UNDER |
| P6 | $PROG_{100} = 14.6\ AUW^{.817}\ CLIMB^{.326}$ (.000) (.000) | .82 | .35 | 66 | 32 | +8 | -81 | -8 | +4 | 25 | RP:CUR:UNDER |
| P7 | $PROG_{100} = 2.19\ EW^{.828}\ SP^{.696}$ (.000) (.000) | .88 | .29 | 102 | 32 | +24 | -58 | -6 | +9 | 24 | RP:CUR:UNDER |

Table 13 (continued)

| Eq. No. | Equation | $R^2$ | SEE | F | N | A-10 | C-141 | F-14 | F-15 | Abs Avg | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Statistics | | | | Relative Deviations (%) | | | | | |
| P8 | $PROG_{100} = 187\ EW^{.813}_{(.000)}\ SPCLS^{.596}_{(.000)}$ | .88 | .28 | 107 | 32 | +11 | -52 | 0 | +13 | 19 | RP:CUR:UNDER |
| P9 | $PROG_{100} = 7.38\ EW^{.869}_{(.000)}\ CLIMB^{.308}_{(.000)}$ | .85 | .32 | 82 | 32 | +15 | -80 | -2 | +5 | 26 | RP:CUR:UNDER |
| P10 | $PROG_{100} = 3.21\ WTAREA^{.848}_{(.000)}\ SP^{.910}_{(.000)}$ | .83 | .32 | 65 | 29 | +17 | -61 | -10 | -7 | 24 | RP:CUR:UNDER 10:S-3 |
| P11 | $PROG_{100} = 1390\ WTAREA^{.795}_{(.000)}\ SPCLS^{.725}_{(.000)}$ | .82 | .34 | 58 | 29 | -5 | -50 | -1 | +2 | 14 | RP:CUR:UNDER |
| P12 | $PROG_{100} = 26.1\ WTAREA^{.869}_{(.000)}\ CLIMB^{.392}_{(.000)}$ | .77 | .38 | 43 | 29 | 0 | -87 | -5 | -14 | 26 | RP:CUR:UNDER |
| | SIZE/PERFORMANCE/CONSTRUCTION | | | | | | | | | | |
| P13 | $PROG_{100} = 12.1\ /UW^{.768}_{(.000)}\ SP^{.534}_{(.002)}\ WGTYPE^{.367}_{(.039)}$ | .87 | .30 | 62 | 32 | +29 | -66 | -26 | +20 | 35 | RP:CUR:UNDER |
| P14 | $PROG_{100} = 3.87\ AUW^{.855}_{(.000)}\ SP^{.663}_{(.000)}\ EWAUW^{.372}_{(.020)}$ | .87 | .29 | 65 | 32 | +24 | -60 | -4 | +8 | 24 | RP:CUR:UNDER |

Table 13 (continued)

| Eq. No. | Equation | Statistics $R^2$ | SEE | F | N | Relative Deviations (%) A-10 | C-141 | F-14 | F-15 | Abs Avg | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| P15 | $PROG_{100} = 9.02\ AUW^{.883}_{(.000)}\ SP^{.554}_{(.000)}\ AVAUW^{.283}_{(.001)}$ | .90 | .26 | 66 | 27 | +27 | -41 | -13 | +17 | 24 | RP:CUR:UNDER |
| P16 | $PROG_{100} = 7.60\ AUW^{.652}_{(.000)}\ SP^{.703}_{(.000)}\ BLBOX^{.302}_{(.014)}$ | .88 | .29 | 65 | 31 | +11 | -60 | -23 | -10 | 26 | MCOL:r(AUW) > .7<br>IO:A-7 |
| P17 | $PROG_{100} = 37.5\ AUW^{.793}_{(.000)}\ CLIMB^{.212}_{(.005)}\ WGTYPE^{.526}_{(.003)}$ | .86 | .31 | 59 | 32 | +29 | -84 | -32 | +21 | 42 | |
| P18 | $PROG_{100} = 11.9\ AUW^{.909}_{(.000)}\ CLIMB^{.290}_{(.000)}\ EWAUW^{.464}_{(.009)}$ | .85 | 32 | 55 | 32 | +18 | -81 | +1 | +4 | 26 | RP:CUR:UNDER |
| P19 | $PROG_{100} = 17.3\ AUW^{.938}_{(.000)}\ CLIMB^{.272}_{(.000)}\ AVAUW^{.339}_{(.000)}$ | .90 | .26 | 68 | 27 | +26 | -48 | -16 | +11 | 25 | RP:CUR:UNDER |
| P20 | $PROG_{100} = 3.67\ EW^{.934}_{(.000)}\ SP^{.543}_{(.000)}\ AVAUW^{.241}_{(.003)}$ | .90 | .25 | 72 | 27 | +32 | -46 | -6 | +16 | 25 | RP:CUR:UNDER |
| P21 | $PROG_{100} = 4.70\ EW^{.701}_{(.000)}\ SP^{.665}_{(.000)}\ BLBOX^{.288}_{(.011)}$ | .90 | .27 | 79 | 31 | +16 | -61 | -16 | -8 | 25 | IO:A-7 |
| P22 | $PROG_{100} = 17.8\ EW^{.842}_{(.000)}\ CLIMB^{.212}_{(.003)}\ WGTYPE^{.434}_{(.008)}$ | .88 | .29 | 67 | 32 | +31 | -81 | -20 | +19 | 38 | RP:CUR:UNDER |

Table 13 (continued)

| Eq. No. | Equation | Statistics $R^2$ | SEE | F | N | Relative Deviations (%) A-10 | C-141 | F-14 | F-15 | Abs Avg | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| P23 | $PROG_{100} = 7.59\ EW^{.985}_{(.000)}\ CLIMB^{.257}_{(.000)}\ AVAUW^{.293}_{(.001)}$ | .90 | .25 | 70 | 27 | +30 | -53 | -7 | +11 | 25 | RP:CUR:UNDER |
| | <u>SIZE/PERFORMANCE/PROGRAM</u> | | | | | | | | | | |
| P24 | $PROG_{100} = 2.01\ AUW^{.795}_{(.000)}\ SP^{.793}_{(.000)}\ EXPDV^{.349}_{(.017)}$ | .88 | .29 | 66 | 32 | +8 | -45 | -6 | +14 | 18 | |
| P25 | $PROG_{100} = 6.83\ AUW^{.844}_{(.000)}\ CLIMB^{.366}_{(.000)}\ EXPDV^{.406}_{(.014)}$ | .85 | .32 | 53 | 32 | -4 | -66 | -2 | +9 | 20 | RP:CUR:UNDER |
| P26 | $PROG_{100} = 1.15\ EW^{.848}_{(.000)}\ SP^{.747}_{(.000)}\ EXPDV^{.377}_{(.006)}$ | .90 | .26 | 85 | 32 | +14 | -44 | +1 | +15 | 18 | RP:CUR:UNDER |
| P27 | $PROG_{100} = 10.4\ EW^{.771}_{(.000)}\ SP^{.564}_{(.000)}\ PRGDV^{-.338}_{(.029)}$ | .89 | .27 | 76 | 32 | +26 | -68 | -6 | +7 | 27 | RP:CUR:UNDER |
| P28 | $PROG_{100} = 3.14\ EW^{.902}_{(.000)}\ CLIMB^{.351}_{(.000)}\ EXPDV^{.436}_{(.005)}$ | .88 | .29 | 70 | 32 | +4 | -64 | +4 | +10 | 20 | RP:CUR:UNDER |
| P29 | $PROG_{100} = 38.7\ EW^{.788}_{(.000)}\ CLIMB^{.235}_{(.001)}\ PRGDV^{-.422}_{(.013)}$ | .87 | .29 | 65 | 32 | +21 | -88 | -3 | +3 | 29 | RP:CUR:UNDER |

Table 13 (continued)

| Eq. No. | Equation | Statistics $R^2$ | SEE | F | N | Relative Deviations (%) A-10 | C-141 | F-14 | F-15 | Abs Avg | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | SIZE/PERFORMANCE/CONSTRUCTION/PROGRAM | | | | | | | | | | |
| P30 | $PROG_{100} = 7.91\ AUW^{.785}_{(.000)}\ SP^{.550}_{(.001)}\ WGTYPE^{.432}_{(.013)}\ EXPDV^{.395}_{(.006)}$ | .90 | .27 | 59 | 32 | +21 | -52 | -20 | +28 | 30 | |
| P31 | $PROG_{100} = 4.00\ AUW^{.838}_{(.000)}\ SP^{.671}_{(.000)}\ EWAUW^{.380}_{(.016)}\ ENGDV^{.248}_{(.053)}$ | .89 | .28 | 53 | 32 | +31 | -42 | +5 | -1 | 20 | RP:CUR:UNDER<br>VAR SIG:ENGDV |
| P32 | $PROG_{100} = 2.15\ AUW^{.874}_{(.000)}\ SP^{.710}_{(.000)}\ EWAUW^{.385}_{(.011)}\ EXPDV^{.361}_{(.010)}$ | .90 | .27 | 60 | 32 | +15 | -47 | +3 | +14 | 20 | RP:CUR:UNDER |
| P33 | $PROG_{100} = 23.9\ AUW^{.801}_{(.000)}\ SP^{.491}_{(.001)}\ EWAUW^{.431}_{(.007)}\ PRGDV^{-.393}_{(.017)}$ | .89 | .27 | 57 | 32 | +28 | -72 | -2 | +6 | 27 | RP:CUR:UNDER |
| P34 | $PROG_{100} = 3.98\ AUW^{.692}_{(.000)}\ SP^{.755}_{(.000)}\ BLBOX^{.235}_{(.042)}\ EXPDV^{.285}_{(.044)}$ | .89 | .28 | 54 | 31 | +5 | -48 | -14 | 0 | 17 | MCOL:r(AUW) > .7 |
| P35 | $PROG_{100} = 17.3\ AUW^{.822}_{(.000)}\ CLIMB^{.247}_{(.001)}\ WGTYPE^{.577}_{(.000)}\ EXPDV^{.462}_{(.002)}$ | .90 | .27 | 61 | 32 | +20 | -66 | -26 | +27 | 35 | RP:CUR:UNDER |
| P36 | $PROG_{100} = 11.3\ AUW^{.892}_{(.000)}\ CLIMB^{.303}_{(.000)}\ EWAUW^{.469}_{(.006)}\ ENGDV^{.294}_{(.038)}$ | .87 | .30 | 45 | 32 | +27 | -57 | +10 | -9 | 26 | RP:CUR:UNDER |
| P37 | $PROG_{100} = 5.41\ AUW^{.940}_{(.000)}\ CLIMB^{.330}_{(.000)}\ EWAUW^{.477}_{(.004)}\ EXPDV^{.419}_{(.006)}$ | .88 | .29 | 52 | 32 | +8 | -65 | +6 | +9 | 22 | RP:CUR:UNDER |

Table 13 (continued)

| Eq. No. | Equation | Statistics $R^2$ | SEE | F | N | Relative Deviations (%) A-10 | C-141 | F-14 | F-15 | Abs Avg | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| P38 | $PROG_{100} = 72.5\ \underset{(.000)}{AUW^{.829}}\ \underset{(.004)}{CLIMB^{.202}}\ \underset{(.003)}{EWAUW^{.505}}\ \underset{(.006)}{PRGDV^{-.470}}$ | .88 | .29 | 52 | 32 | +26 | -90 | +1 | +2 | 30 | RP:CUR:UNDER |
| P39 | $PROG_{100} = 11.5\ \underset{(.000)}{AUW^{.723}}\ \underset{(.000)}{CLIMB^{.363}}\ \underset{(.026)}{BLBOX^{.282}}\ \underset{(.030)}{EXPDV^{.344}}$ | .88 | .30 | 46 | 31 | -7 | -66 | -14 | -10 | 24 | MCOL:r(AUW) > .7 |
| P40 | $PROG_{100} = 3.56\ \underset{(.000)}{EW^{.836}}\ \underset{(.000)}{SP^{.555}}\ \underset{(.026)}{WGTYPE^{.341}}\ \underset{(.002)}{EXPDV^{.411}}$ | .91 | .25 | 72 | 32 | +23 | -50 | -9 | +26 | 27 | |
| P41 | $PROG_{100} = 2.19\ \underset{(.000)}{EW^{.751}}\ \underset{(.000)}{SP^{.721}}\ \underset{(.040)}{BLBOX^{.212}}\ \underset{(.017)}{EXPDV^{.319}}$ | .91 | .25 | 70 | 31 | +10 | -47 | -6 | +3 | 16 | MCOL:r(EW) > .7 |
| P42 | $PROG_{100} = 7.64\ \underset{(.000)}{EW^{.874}}\ \underset{(.000)}{CLIMB^{.248}}\ \underset{(.001)}{WGTYPE^{.483}}\ \underset{(.001)}{EXPDV^{.479}}$ | .92 | .24 | 75 | 32 | +23 | -63 | -14 | +25 | 31 | RP:CUR:UNDER |
| P43 | $PROG_{100} = 3.59\ \underset{(.000)}{EW^{.990}}\ \underset{(.000)}{CLIMB^{.308}}\ \underset{(.003)}{AVAUW^{.240}}\ \underset{(.039)}{EXPDV^{.306}}$ | .91 | .24 | 59 | 27 | +21 | -48 | -4 | +11 | 21 | RP:CUR:UNDER |

# XII. SELECTION OF RECOMMENDED EQUATION SET

## SUMMARY OF PRECEDING ANALYSIS

The representative equation sets for the four size/performance variable combinations (airframe unit weight/speed, airframe unit weight/climb rate, empty weight/speed, and empty weight/climb rate) as well as the equation set containing the "best" estimating relationship for each cost element (irrespective of the size/performance variable combination) are listed in Tables 14 through 18. A comparison of these equation sets based on the relative deviations of four relatively recent sample aircraft (A-10, C-141, F-14, and F-15) is provided in Table 19. On review of these tables, the following observations are made:

1. There is little difference in the statistical quality of the sets.

2. The engineering, manufacturing material, development support, and total program cost equations in each set show a tendency to underestimate the costs of the most recent sample aircraft.

3. On the basis of comparisons of: (a) the standard errors of estimate of individual estimating relationships, and (b) relative deviations with respect to the A-10, C-141, F-14, and F-15 (Table 19), there does not appear to be any advantage in mixing the set size/performance variables.

4. Based on comparisons of the A-10, C-141, F-14, and F-15, the estimates obtained by summing the individual elements are in remarkably close agreement with the estimates determined by the total program CERs.

5. With the exception of the number of test aircraft (for the flight test cost element), the construction/program variables were not an influential factor in reducing the standard errors of estimate of individual estimating relationships.

Table 14

REPRESENTATIVE SET: AIRFRAME UNIT WEIGHT AND SPEED

| Estimating Relationship | $R^2$ | SEE | F | N | Residual Pattern |
|---|---|---|---|---|---|
| $ENGR_{100} = .00445\ AUW^{.758}\ SP^{1.03}$ (.000) (.000) | .71 | .49 | 36 | 32 | CUR:UNDER |
| $TOOL_{100} = .127\ AUW^{.699}\ SP^{.609}$ (.000) (.001) | .74 | .40 | 41 | 32 | None |
| $LABR_{100} = .329\ AUW^{.801}\ SP^{.429}$ (.000) (.002) | .86 | .31 | 88 | 32 | None |
| $MATL_{100} = .0999\ AUW^{.895}\ SP^{.811}$ (.000) (.000) | .84 | .38 | 77 | 32 | CUR:UNDER |
| $DS = .00761\ AUW^{.761}\ SP^{1.28}$ (.000) (.001) | .50 | .82 | 15 | 32 | CUR:UNDER |
| $FT = .00617\ AUW^{.584}\ SP^{1.27}\ TESTAC^{.805}$ (.000) (.000)(.002) | .71 | .60 | 23 | 32 | None |
| $QC_{100} = .065 * LABR_{100}$ if cargo aircraft | -- | -- | -- | -- | -- |
| $= .125 * LABR_{100}$ if non-cargo aircraft | | | | | |
| $PROG_{100} = 3.56\ AUW^{.779}\ SP^{.745}$ (.000) (.000) | .85 | .31 | 85 | 32 | CUR:UNDER |

Table 15

REPRESENTATIVE SET: AIRFRAME UNIT WEIGHT AND CLIMB RATE

| Estimating Relationship | $R^2$ | SEE | F | N | Residual Pattern |
|---|---|---|---|---|---|
| $ENGR_{100} = .0150\ AUW^{.830}\ CLIMB^{.510}$ <br> (.000) (.000) | .71 | .49 | 36 | 32 | CUR:UNDER |
| $TOOL_{100} = .502\ AUW^{.724}\ CLIMB^{.249}$ <br> (.000) (.005) | .70 | .43 | 34 | 32 | None |
| $LABR_{100} = .757\ AUW^{.822}\ CLIMB^{.186}$ <br> (.000) (.006) | .85 | .32 | 80 | 32 | None |
| $MATL_{100} = .686\ AUW^{.927}\ CLIMB^{.325}$ <br> (.000) (.001) | .79 | .43 | 56 | 32 | CUR:UNDER |
| $DS = .0780\ AUW^{.829}\ CLIMB^{.567}$ <br> (.000) (.002) | .46 | .85 | 12 | 32 | CUR:UNDER |
| $FT = .0859\ AUW^{.641}\ CLIMB^{.512}\ TESTAC^{.916}$ <br> (.000) (.002) (.001) | .65 | .66 | 18 | 32 | None |
| $QC_{100} = .085 * LABR_{100}$ if cargo aircraft <br> $= .125 * LABR_{100}$ if non-cargo aircraft | -- | -- | -- | -- | -- |
| $PROG_{100} = 14.6\ AUW^{.817}\ CLIMB^{.326}$ <br> (.000) (.000) | .82 | .35 | 66 | 32 | CUR:UNDER |

Table 16

REPRESENTATIVE SET: EMPTY WEIGHT AND SPEED

| Estimating Relationship | $R^2$ | SEE | F | N | Residual Pattern |
|---|---|---|---|---|---|
| $ENGR_{100} = .00355\ EW^{.787}\ SP^{.980}$<br>(.000)(.000) | .70 | .50 | 34 | 32 | CUR:UNDER |
| $TOOL_{100} = .0695\ EW^{.755}\ SP^{.570}$<br>(.000)(.001) | .78 | .37 | 52 | 32 | None |
| $LABR_{100} = .198\ EW^{.852}\ SP^{.379}$<br>(.000)(.002) | .88 | .28 | 109 | 32 | None |
| $MATL_{100} = .0623\ EW^{.945}\ SP^{.752}$<br>(.000)(.000) | .85 | .36 | 83 | 32 | CUR:UNDER |
| $DS = .00417\ EW^{.818}\ SP^{1.23}$<br>(.000)(.001) | .52 | .80 | 16 | 32 | CUR:UNDER |
| $FT = .00293\ EW^{.644}\ SP^{1.27}\ TESTAC^{.767}$<br>(.000)(.000)(.002) | .74 | .58 | 26 | 32 | CUR:UNDER |
| $QC_{100} = .085 * LABR_{100}$ if cargo aircraft<br>$= .125 * LABR_{100}$ if non-cargo aircraft | -- | -- | -- | -- | -- |
| $PROG_{100} = 2.19\ EW^{.828}\ SP^{.696}$<br>(.000)(.000) | .88 | .29 | 102 | 32 | CUR:UNDER |

Table 17

REPRESENTATIVE SET: EMPTY WEIGHT AND CLIMB RATE

| Estimating Relationship | $R^2$ | SEE | F | N | Residual Pattern |
|---|---|---|---|---|---|
| $ENGR_{100} = .0100\ EW^{.862}\ CLIMB^{.485}$ <br> (.000)(.000) | .70 | .50 | 34 | 34 | CUR:UNDER |
| $TOOL_{100} = .227\ EW^{.784}\ CLIMB^{.238}$ <br> (.000)(.004) | .75 | .39 | 44 | 32 | None |
| $LABR_{100} = .383\ EW^{.874}\ CLIMB^{.168}$ <br> (.000)(.005) | .87 | .29 | 101 | 32 | None |
| $MATL_{100} = .345\ EW^{.980}\ CLIMB^{.303}$ <br> (.000)(.001) | .85 | .36 | 85 | 32 | CUR:UNDER |
| $DS = .0331\ EW^{.894}\ CLIMB^{.553}$ <br> (.000)(.002) | .49 | .83 | 14 | 32 | CUR:UNDER |
| $FT = .0332\ EW^{.877}\ CLIMB^{.571}\ AVAUW^{.488}\ TESTAC^{.491}$ <br> (.000)(.000) (.006) (.049) | .71 | .56 | 13 | 27 | None |
| $QC_{100} = .085 * LABR_{100}$ if cargo aircraft <br> $= .125 * LABR_{100}$ if non-cargo aircraft | -- | -- | -- | -- | -- |
| $PROG_{100} = 7.38\ EW^{.869}\ CLIMB^{.308}$ <br> (.000)(.000) | .85 | .32 | 82 | 32 | CUR:UNDER |

Table 18

REPRESENTATIVE SET: SINGLE BEST EQUATION FOR EACH COST ELEMENT

| Estimating Relationship | $R^2$ | SEE | F | N | Residual Pattern |
|---|---|---|---|---|---|
| $ENGR_{100} = 3.26\ AUW^{.733}\ SPCLS^{.925}$ (.000)(.000) | .74 | .46 | 42 | 32 | CUR:UNDER |
| $TOOL_{100} = .0695\ EW^{.755}\ SP^{.570}$ (.000)(.001) | .78 | .37 | 52 | 32 | None |
| $LABR_{100} = .198\ EW^{.852}\ SP^{.379}$ (.000)(.002) | .88 | .28 | 109 | 32 | None |
| $MATL_{100} = .0623\ EW^{.945}\ SP^{.752}$ (.000)(.000) | .85 | .36 | 83 | 32 | CUR:UNDER |
| $DS = 10.5\ EW^{.794}\ SPCLS^{1.08}$ (.000)(.000) | .54 | .78 | 17 | 32 | CUR:UNDER |
| $FT = .00293\ EW^{.644}\ SP^{1.27}\ TESTAC^{.767}$ (.000)(.000)(.002) | .74 | .58 | 26 | 32 | None |
| $QC_{100} = .085 * LABR_{100}$ if cargo aircraft | -- | -- | -- | -- | -- |
| $= .125 * LABR_{100}$ if non-cargo aircraft | | | | | |
| $PROG_{100} = 2.19\ EW^{.828}\ SP^{.696}$ (.000)(.000) | .88 | .29 | 102 | 32 | CUR:UNDER |

Table 19

RELATIVE PERCENTAGE DIFFERENCES BETWEEN ACTUALS AND REPRESENTATIVE EQUATION SET ESTIMATES (a)

| Aircraft | AUW/SPEED (Table 14) | AUW/CLIMB (Table 15) | EW/SPEED (Table 16) | EW/CLIMB (Table 17) | Best Size/ Performance (Table 18) |
|---|---|---|---|---|---|
| Sum of Individual CERs (b) | | | | | |
| A-10 | +17 | + 9 | +23 | +16 | +19 |
| C-141 | -53 | -73 | -54 | -73 | -51 |
| F-14 | -12 | - 7 | - 5 | - 4 | - 4 |
| F-15 | + 5 | 0 | + 5 | + 1 | + 7 |
| Average (absolute) | 22 | 22 | 22 | 24 | 20 |
| Total Program CER | | | | | |
| A-10 | +18 | + 8 | +23 | +16 | +23 |
| C-141 | -58 | -80 | -58 | -79 | -58 |
| F-14 | -13 | - 8 | - 6 | - 1 | - 6 |
| F-15 | + 8 | + 5 | + 9 | + 5 | + 9 |
| Average (absolute) | 24 | 25 | 24 | 25 | 24 |

(a)(Actual-Estimate)/Actual
(b)Hourly labor rates applied to those cost elements estimated in hours are as follows: engineering, 27.50; tooling, 25.50; manufacturing labor, 23.50; and quality control, 24.00.

Since there is little, if any, advantage to mixing the set size/performance variables, the recommended equation set will be chosen from among the four sets that maintain the integrity of the size/performance variable combination. Of these four sets, the two using speed (AUW/SP and EW/SP) have slightly better statistical properties than the two sets using climb rate. Of the two sets using speed, the empty weight/speed set (Table 16) is selected as the "recommended" set because of the lower standard errors of estimate with respect to several of the cost elements, plus the fact that empty weight is generally a more readily available input than airframe unit weight.

The estimating relationships in the recommended equation set vary significantly in statistical quality. Although none of the seven CERs reaches our standard of estimate goal of 0.18, the best estimating relationships are generally associated with the largest contributors to total cost:

| Cost Element | Percent of Total Cost at Q = 100 | Standard Error of Estimate |
|---|---|---|
| Engineering | 19 | .50 |
| Tooling | 16 | .37 |
| Manufacturing labor | 34 | .28 |
| Manufacturing material | 16 | .36 |
| Development support | 5 | .80 |
| Flight test | 6 | .58 |
| Quality control | 4 | |
| | 100 | |

## ADDITIONAL ANALYSIS

As stated above, the engineering, manufacturing material, development support, flight test, and total program cost equations tend to underestimate the costs of the most recent sample aircraft. We believe this difficulty stems from the combined effects of numerous design-related and institutional changes that have occurred over the

1948-1978 time period (e.g., the increased emphasis on electronics as well as changes in materials of construction, manufacturing processes, and the regulatory framework). Our original plan was to develop specific measures that would reflect these changes. Unfortunately, this approach did not prove to be as successful as we would have liked. For many of the more abstract concepts we could not develop unambiguous measures. And even for the concepts for which relatively unambiguous measures could be developed and tested, the results were marginal at best. Consequently, two alternative approaches were investigated:

1. Deletion of older, less relevant aircraft from the sample; and,
2. Incorporation of a time variable into those equations exhibiting the underestimation problem.

### Deletion of Older Aircraft

All aircraft with first flight dates before 1960 were deleted from the sample.[1] The remaining 11 post-1960 aircraft were the A-6, A-7, A-10, C-5, C-141, F-4, F-111, F-14, F-15, S-3, and T-39.

A comparison of a few of the key variables for the original full sample and the new post-1960 sample is provided in Table 20. Generally speaking, the post-1960 sample has larger means and standard deviations.

A comparison of the basic 32-aircraft equation set and an analogous equation set based only on the 11 post-1960 aircraft is provided in Table 21. As indicated, the standard errors of estimate for three cost elements decreased somewhat (tooling, material, and flight test) and increased somewhat for the remainder (engineering, labor, development support, and total program cost). Additionally, two of the residual patterns are eliminated but three remain.

[1]The choice of 1960 as a breakpoint is not intended to imply a hard and fast distinction between the pre-1960 and post-1960 aircraft. Rather, it more correctly represents a balance between eliminating older, potentially irrelevant observations on the one hand, and attempting to maintain some semblance of an acceptable sample size on the other.

Table 20

COMPARISON OF TOTAL AND POST-1960 VARIABLE VALUES

| Variable | Total Sample | Post-1960 Sample | Total Sample | Post-1960 Sample | Total Sample | Post-1960 Sample |
|---|---|---|---|---|---|---|
| Airframe unit weight (lb) | 35237 | 49733 | 52769 | 80651 | 5072-279145 | 7027-279145 |
| Empty weight (lb) | 47815 | 62845 | 63306 | 92083 | 7410-320085 | 9753-320085 |
| Wetted area (sq ft) | 5091 | 6429 | 6475 | 9324 | 1070-30800 | 1690--30800 |
| Speed (kn) | 734 | 777 | 320 | 403 | 304-1250+ | 389-1250+ |
| Climb rate (ft/min) | 17942 | 18916 | 16129 | 20796 | 3400-50000+ | 4270-50000+ |
| AVAUW | .094 | .091 | .058 | .064 | .016-.220 | .017-.220 |
| EWAUW | 47 | .40 | .17 | .12 | .15-.84 | .15-.60 |
| Number of black boxes | 15 | 21 | 8 | 7 | 4-33 | 10-33 |

Table 21

COMPARISON OF BASIC 32-AIRCRAFT EQUATION SET TO EQUATION SET BASED ON SAMPLE OF 11 POST-1960 AIRCRAFT

| Equation | $R^2$ | SEE | F | N | Residual Pattern |
|---|---|---|---|---|---|
| **Part A: 32-Aircraft Sample (from Table 16)** | | | | | |
| $ENGR_{100} = .00355\ EW^{.787}\ SP^{.980}$ (.000)(.000) | .70 | .50 | 34 | 32 | CUR:UNDER |
| $TOOL_{100} = .0695\ EW^{.755}\ SP^{.570}$ (.000)(.000) | .78 | .37 | 52 | 32 | None |
| $LABR_{100} = .198\ EW^{.852}\ SP^{.379}$ (.000)(.002) | .88 | .28 | 109 | 32 | None |
| $MATL_{100} = .0623\ EW^{.945}\ SP^{.752}$ (.000)(.000) | .85 | .36 | 83 | 32 | CUR:UNDER |
| $DS = .00417\ EW^{.818}\ SP^{1.23}$ (.000)(.001) | .52 | .80 | 16 | 32 | CUR:UNDER |
| $FT = .00293\ EW^{.644}\ SP^{1.27}\ TESTAC^{.767}$ (.000)(.000)(.002) | .74 | .58 | 26 | 32 | CUR:UNDER |
| $QC_{100} = .085 * LABR_{100}$ if cargo aircraft | -- | -- | -- | 3 | -- |
| $= .125 * LABR_{100}$ if non-cargo aircraft | -- | -- | -- | 17 | -- |
| $PROG_{100} = 2.19\ EW^{.828}\ SP^{.696}$ (.000)(.000) | .88 | .29 | 102 | 32 | CUR:UNDER |
| **Part B: 11 Post-1960 Aircraft** | | | | | |
| $ENGR_{100} = .0133\ EW^{.811}\ SP^{.793}$ (.001)(.030) | .75 | .57 | 12 | 11 | CUR:UNDER |
| $TOOL_{100} = .0221\ EW^{.778}\ SP^{.680}$ (.000)(.002) | .93 | .26 | 52 | 11 | None |
| $LABR_{100} = .165\ EW^{.820}\ SP^{.456}$ (.000)(.018) | .91 | .29 | 42 | 11 | None |
| $MATL_{100} = .299\ EW^{.954}\ SP^{.526}$ (.000)(.008) | .94 | .27 | 64 | 11 | None |
| $DS = .0323\ EW^{.660}\ SP^{1.21}$ (.026)(.033) | .54 | .90 | 5 | 11 | CUR:UNDER |
| $FT = .596\ EW^{.336}\ SP^{.858}\ TESTAC^{1.11}$ (.038)(.040)(.020) | .85 | .48 | 14 | 11 | None |
| $QC_{100} = .076 * LABR_{100}$ if cargo aircraft | -- | -- | -- | 2 | -- |
| $= .126 * LABR_{100}$ if non-cargo aircraft | -- | -- | -- | 9 | -- |
| $PROG_{100} = 3.12\ EW^{.814}\ SP^{.676}$ (.000)(.008) | .88 | .35 | 30 | 11 | CUR:UNDER |

## Incorporation of Time Variable

The second approach for eliminating time-dependent residual patterns is to introduce a time variable into the estimating relationship--in this case, the date of first flight measured in months since January 1, 1940. The use of a cumulative time variable in a CER is not a new idea (e.g., see Ref. 3). Such measures are typically used when it is not otherwise possible to characterize the changes in cost that have occurred over time. Invariably, they capture the *combined* effect of shifts in many diverse factors including, for example: the regulatory framework; aircraft "quality" (factors not directly related to speed such as maneuvering capability, the materials of construction, and the level of system integration); and improvements in production technology and labor productivity. Consequently, when using an equation incorporating a time variable to estimate the cost of a future aircraft, the analyst must ensure that the same factors will be operating in the future as operated in the past and in the same manner. Clearly, the opaque nature of such time variables makes this a non-trivial task.

After an examination of the relevant full sample residual plots, two forms of the first flight date (FFD) were examined--linear and logarithmic. Given the logarithmic form of the dependent variable, the linear form of FFD results in an accelerating rate of cost increase (assuming an FFD coefficient greater than zero), whereas the logarithmic form of FFD results in a decelerating rate of cost increase (assuming an FFD exponent of less than one). Unfortunately, we have no a priori notions with respect to whether the rate of increase is rising or falling.

The results are provided in Part B of Tables 22 and 23. As indicated, the residual patterns have been eliminated in each of the five cost elements previously exhibiting such a pattern (engineering, material, development support, flight test, and total program cost). Moreover, the standard errors of estimate have been reduced in each instance where the time variable was introduced. Finally, from a statistical standpoint, it should be noted that the two equation sets incorporating the alternative forms of first flight date are essentially equivalent.

Table 22

COMPARISON OF BASIC 32-AIRCRAFT EQUATION SET TO ANALOGOUS EQUATION SET INCORPORATING TIME VARIABLE (LINEAR FORM)

| Equation | $R^2$ | SEE | F | N | Residual Pattern |
|---|---|---|---|---|---|
| Part A: 32-Aircraft Sample Without Time Variable (from Table 16) | | | | | |
| $ENGR_{100} = .00355\ EW^{.787}\ SP^{.980}$ (.000)(.000) | .70 | .50 | 34 | 32 | CUR:UNDER |
| $TOOL_{100} = .0695\ EW^{.755}\ SP^{.570}$ (.000)(.001) | .78 | .37 | 52 | 32 | None |
| $LABR_{100} = .198\ EW^{.852}\ SP^{.379}$ (.000)(.002) | .88 | .28 | 109 | 32 | None |
| $MATL_{100} = .0623\ EW^{.945}\ SP^{.752}$ (.000)(.000) | .85 | .36 | 83 | 32 | CUR:UNDER |
| $DS = .00417\ EW^{.818}\ SP^{1.23}$ (.000)(.001) | .52 | .80 | 16 | 32 | CUR:UNDER |
| $FT = .00293\ EW^{.644}\ SP^{1.27}\ TESTAC^{.767}$ (.000)(.000)(.002) | .74 | .58 | 26 | 32 | CUR:UNDER |
| $QC_{100} = .085 * LABR_{100}$ if cargo aircraft | -- | -- | -- | 3 | -- |
| $= .125 * LABR_{100}$ if non-cargo aircraft | -- | -- | -- | 17 | -- |
| $PROG_{100} = 2.19\ EW^{.828}\ SP^{.696}$ (.000)(.000) | .88 | .29 | 102 | 32 | CUR:UNDER |
| Part B: 32-Aircraft Sample with Time Variable (Linear Form) Added | | | | | |
| $ENGR_{100} = .00866\ EW^{.696}\ SP^{.829}\ e^{.00421 \times FFD}$ (.000)(.000) (.000) | .84 | .37 | 51 | 32 | None |
| $TOOL_{100} = .0695\ EW^{.755}\ SP^{.570}$ (.000)(.001) | .78 | .37 | 52 | 32 | None |
| $LABR_{100} = .198\ EW^{.852}\ SP^{.379}$ (.000)(.002) | .88 | .28 | 109 | 32 | None |
| $MATL_{100} = .111\ EW^{.888}\ SP^{.656}\ e^{.00267 \times FFD}$ (.000)(.000) (.000) | .91 | .29 | 90 | 32 | None |
| $DS = .00916\ EW^{.739}\ SP^{1.10}\ e^{.00365 \times FFD}$ (.000)(.001) (.020) | .59 | .75 | 14 | 32 | None |
| $FT = .00779\ EW^{.573}\ SP^{1.05}\ TESTAC^{.915}\ e^{.00322 \times FFD}$ (.000)(.000)(.000) (.007) | .79 | .52 | 25 | 32 | None |
| $QC_{100} = .085 * LABR_{100}$ if cargo aircraft | -- | -- | -- | 3 | -- |
| $= .125 * LABR_{100}$ if non-cargo aircraft | -- | -- | -- | 17 | -- |
| $PROG_{100} = 2.96\ EW^{.799}\ SP^{.647}\ e^{.00136 \times FFD}$ (.000)(.000) (.017) | .89 | .27 | 79 | 32 | None |

Table 23

COMPARISON OF BASIC 32-AIRCRAFT EQUATION SET TO ANALOGOUS EQUATION SET INCORPORATING TIME VARIABLE (LOGARITHMIC FORM)

| Equation | $R^2$ | SEE | F | N | Residual Pattern |
|---|---|---|---|---|---|
| **Part A: 32-Aircraft Sample Without Time Variable (from Table 16)** | | | | | |
| $ENGR_{100} = .00355\ EW^{.787}\ SP^{.980}$ (.000)(.000) | .70 | .50 | 34 | 32 | CUR:UNDER |
| $TOOL_{100} = .0695\ EW^{.755}\ SP^{.570}$ (.000)(.001) | .78 | .37 | 52 | 32 | None |
| $LABR_{100} = .198\ EW^{.852}\ SP^{.379}$ (.000)(.002) | .88 | .28 | 109 | 32 | None |
| $MATL_{100} = .0623\ EW^{.945}\ SP^{.752}$ (.000)(.000) | .85 | .36 | 83 | 32 | CUR:UNDER |
| $DS = .00417\ EW^{.818}\ SP^{1.23}$ (.000)(.001) | .52 | .80 | 16 | 32 | CUR:UNDER |
| $FT = .00293\ EW^{.644}\ SP^{1.27}\ TESTAC^{.767}$ (.000)(.000)(.002) | .74 | .58 | 26 | 32 | CUR:UNDER |
| $QC_{100} = .085 * LABR_{100}$ if cargo aircraft | -- | -- | -- | 3 | -- |
| $= .125 * LABR_{100}$ if non-cargo aircraft | -- | -- | -- | 17 | -- |
| $PROG_{100} = 2.19\ EW^{.828}\ SP^{.696}$ (.000)(.000) | .88 | .29 | 102 | 32 | CUR:UNDER |
| **Part B: 32-Aircraft Sample with Time Variable (Logarithmic Form) Added** | | | | | |
| $ENGR_{100} = .000148\ EW^{.677}\ SP^{.791}\ FFD^{1.02}$ (.000)(.000) (.000) | .84 | .36 | 51 | 32 | None |
| $TOOL_{100} = .0695\ EW^{.755}\ SP^{.570}$ (.000)(.001) | .78 | .37 | 52 | 32 | None |
| $LABR_{100} = .198\ EW^{.852}\ SP^{.379}$ (.000)(.002) | .88 | .28 | 109 | 32 | None |
| $MATL_{100} = .00772\ EW^{.872}\ SP^{.627}\ FFD^{.675}$ (.000)(.000) (.000) | .91 | .29 | 95 | 32 | None |
| $DS = .000288\ EW^{.725}\ SP^{1.07}\ FFD^{.863}$ (.000)(.002) (.023) | .59 | .76 | 13 | 32 | None |
| $FT = .000263\ EW^{.546}\ SP^{.986}\ TESTAC^{.944}\ FFD^{.886}$ (.000)(.001)(.000) (.002) | .80 | .50 | 28 | 32 | None |
| $QC_{100} = .085 * LABR_{100}$ if cargo aircraft | -- | -- | -- | 3 | -- |
| $= .125 * LABR_{100}$ if non-cargo aircraft | -- | -- | -- | 17 | -- |
| $PROG_{100} = .747\ EW^{.790}\ SP^{.631}\ FFD^{.350}$ (.000)(.000)(.012) | .90 | .27 | 81 | 32 | None |

## Comparison of Alternative Approaches

**Standard Errors of Estimate.** As shown below, the results with respect to the comparison of standard errors of estimate are mixed. Furthermore, the differences are small and hardly a basis for drawing any conclusions.

| | SEE(log) | | | |
|---|---|---|---|---|
| Cost Element | 32-Aircraft Sample Without Time Variable | 11-Aircraft Post-1960 Sample | 32-Aircraft Sample With Linear FFD | 32-Aircraft Sample With Logarithmic FFD |
| Engineering | .50 | .57 | .37 | .36 |
| Tooling | .37 | .26 | .37 | .37 |
| Manufacturing labor | .28 | .29 | .28 | .28 |
| Manufacturing material | .36 | .27 | .29 | .29 |
| Development support | .80 | .90 | .75 | .76 |
| Flight test | .58 | .48 | .52 | .50 |
| Total program cost | .29 | .35 | .27 | .27 |

**Residual Patterns.** As indicated below, only the equation sets incorporating time variables are completely free of residual patterns.

| | Cost Element Equations Exhibiting Tendency to Underestimate Most Recent Sample Aircraft | | | |
|---|---|---|---|---|
| Cost Element | Basic 32-Aircraft Sample | 11-Aircraft Post-1960 Sample | 32-Aircraft Sample With Linear FFD | 32-Aircraft Sample With Logarithmic FFD |
| Engineering | X | X | -- | -- |
| Tooling | -- | -- | -- | -- |
| Manufacturing labor | -- | -- | -- | -- |
| Manufacturing material | X | -- | -- | -- |
| Development support | X | X | -- | -- |
| Flight test | X | -- | -- | -- |
| Total program cost | X | X | -- | -- |

**Accuracy with Respect to Post-1960 Aircraft.** A comparison of how well each of the four equation sets estimates the 11 post-1960 aircraft is provided in Table 24. On the basis of the overall average of the absolute relative deviations, there is little difference. However, because the underestimates are generally smaller and the overestimates generally larger, it seems reasonable to suggest that the time-modified equation sets will usually produce higher estimates than does the equation set derived from the basic 32-aircraft sample.

## FINAL SELECTION

### Difficulty with Sets Incorporating Time Variable

As just described, the introduction of a time variable solves the underestimation problem and results in equations with relatively good standard errors of estimate. Unfortunately, there is one major difficulty--we are unable to say which of the two FFD forms more accurately reflects industry experience. The statistical analysis, which included an examination of residuals, indicated that the two sets were virtually equivalent in terms of explaining the variation *within* the database. Nevertheless, the inability to distinguish a preferred variable form has significant implications with respect to estimating the costs of future aircraft. As illustrated in Fig. 11, for an aircraft with a projected first flight date of 1995, the difference in assumptions (linear FFD compared with logarithmic FFD) leads to a difference in estimated cost of over 50 percent. Consequently, because of this large variation in projected costs, we do not recommend use of either equation set incorporating the time variable. Rather, we feel it more judicious for analysts to use an equation set without a time variable and to explicitly identify potential changes, estimate their likely effect, and then adjust either the equations or resulting estimates accordingly.

Table 24

PERCENT WHICH ACTUAL COST EXCEEDS (+) OR FALLS SHORT (-)
OF ESTIMATED COST, USING ESTIMATES OBTAINED WITH BASIC 32-AIRCRAFT
EQUATION SET AND ALTERNATIVE SETS INCORPORATING TIME DIMENSION

| | Basic 32-Aircraft Sample | 11-Aircraft Post-1960 Sample | 32-Aircraft Sample with Linear FFD | 32-Aircraft Sample with Logarithmic FFD |
|---|---|---|---|---|
| | Sum of Elements | | | |
| A-6 | +12 | + 2 | + 8 | +11 |
| A-7 | -60 | -79 | -87 | -82 |
| A-10 | +23 | +14 | - 3 | - 7 |
| C-5 | + 8 | + 2 | + 1 | 0 |
| C-141 | -54 | -65 | -60 | -58 |
| F-4 | + 2 | - 6 | + 2 | + 4 |
| F-111 | +16 | + 9 | + 7 | + 7 |
| F-14 | - 5 | -13 | -24 | -28 |
| F-15 | + 5 | - 6 | -19 | -25 |
| T-39 | -19 | -33 | -30 | -26 |
| S-3 | +45 | +39 | +30 | +30 |
| Average Absolute Values | 23 | 24 | 25 | 25 |
| Number Underestimated (+) | 7 | 5 | 5 | 4 |
| Number Overestimated (-) | 4 | 6 | 6 | 6 |
| | Total Program CER | | | |
| A-6 | +11 | + 3 | + 6 | + 8 |
| A-7 | -63 | -79 | -89 | -85 |
| A-10 | +24 | +16 | - 1 | - 3 |
| C-5 | + 7 | + 2 | 0 | - 2 |
| C-141 | -58 | -69 | -66 | -65 |
| F-4 | - 1 | - 8 | - 2 | - 1 |
| F-111 | +17 | +12 | +11 | +10 |
| F-14 | - 6 | -12 | -20 | -23 |
| F-15 | + 9 | + 2 | - 7 | -10 |
| T-39 | -22 | -35 | -35 | -30 |
| S-3 | +45 | +40 | + 3 | +31 |
| Average of Absolute Values | 24 | 25 | 24 | 24 |
| Number Underestimated (+) | 6 | 6 | 3 | 3 |
| Number Overestimated (-) | 5 | 5 | 7 | 8 |

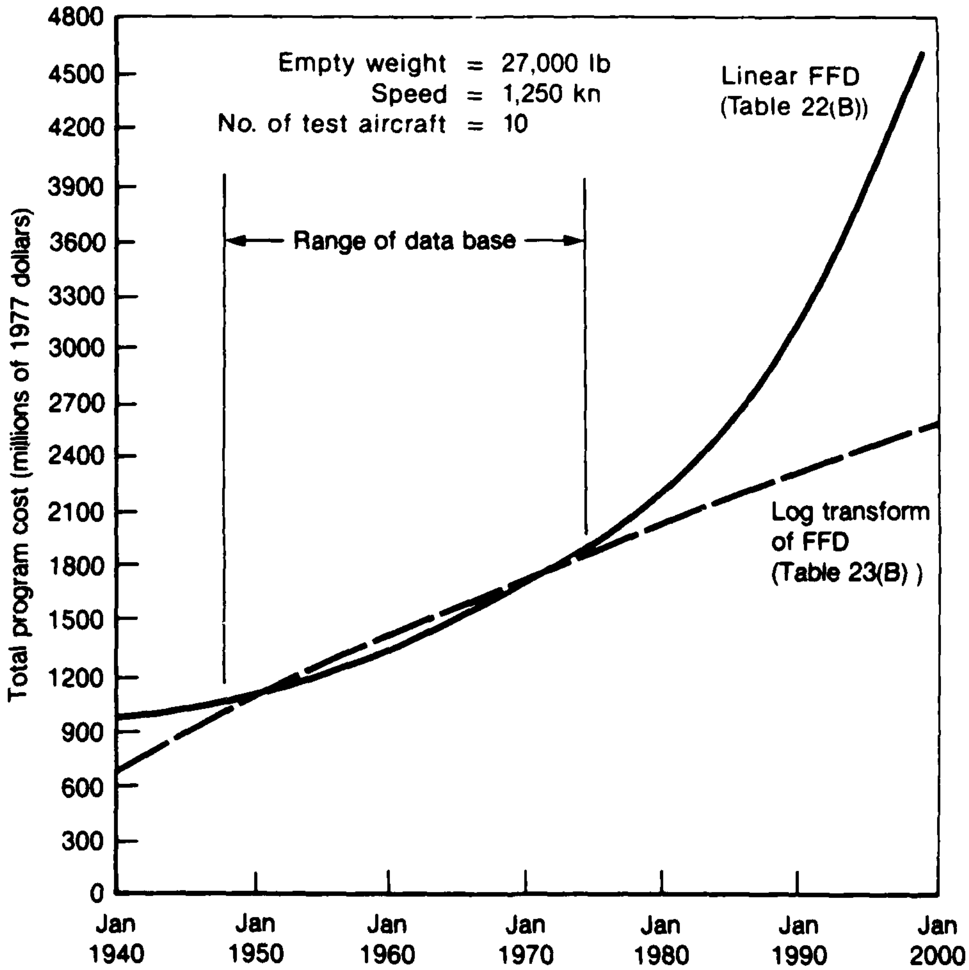



Fig. 11—Total program cost as a function of time
(based on sum of individual elements)

### Choosing Between the Equation Set Based on the 32-Aircraft Estimating Sample and that Sample Based on the 11 Post-1960 Aircraft Sample

We recommend the equation set based on the more limited post-1960 sample of 11 aircraft (Part B of Table 21) for the following reasons:

1. There are fewer estimating relationships that exhibit a tendency to underestimate the most recent sample aircraft; and
2. Because the sample comprises relatively recent aircraft with which most analysts should have some familiarity, the job of adjusting the equations or resulting estimates should be easier.

# XIII. INCORPORATION OF F-16 AND F-18

After completing the detailed analysis heretofore described, but before the publication of this Note, cost data on the F-16 and F-18 airframes became available. Consequently, a brief examination was undertaken to determine whether inclusion of the F-16 and F-18 in the database would dictate modification of the recommended set of CERs (Table 21, Part B). This examination consisted of the following two steps:

1. Assessing how well the existing equation set estimates F-16 and F-18 costs; and,
2. Assessing the stability of variable coefficients when an analogous equation set incorporating the F-16 and F-18 is derived.

## ADJUSTMENT OF F-16 PRODUCTION DATA

Normally, to determine the cumulative total production cost for the first 100 F-16 airframes, we would take recorded data for the two prototypes, eight FSD aircraft, and the first 90 aircraft in the USAF FY77/78 buy of 105 aircraft. However, because of the concurrent multinational coproduction effort (General Dynamics produces all of the forward fuselages and approximately half of all other components), the recurring factory labor and materials cost obtained in that way would be understated because of the additional learning benefit associated with the higher overall production. Therefore, the production labor and material costs for the F-16 are based on 90 "equivalent" aircraft. The estimate for the 90 equivalent aircraft was obtained by taking the costs for the first 90 production units of *each component,* plus the integration and assembly effort for the first 90 aircraft, and then taking their sum.

## USING THE EXISTING EQUATION SET TO ESTIMATE F-16 AND F-18 COSTS

A comparison of F-16 and F-18 actual costs to estimated costs using the CERs provided in Table 21 (Part B) is presented in Table 25.[1] On the basis of this table, the following observations are made:

- Although the relative deviations across cost elements show a fair amount of uniformity in the F-18 case, the same cannot be said for the F-16, where values range from roughly +20 to about -60.
- Especially disturbing is the fact that for the F-18, the two manufacturing cost elements (labor and material) that account for 51 percent of total airframe cost at a quantity of 100 have fairly large deviations--namely, +30 and +50, respectively.
- In total, the full estimating sample equation set overestimates F-16 costs by 10 to 15 percent and underestimates F-18 costs by about 40 percent.

The fact that the F-16 is overestimated and the F-18 underestimated is not all that surprising: The F-16 program placed a great deal of emphasis on maintaining cost goals and the F-18 program faced a particularly involved two-contractor development. Specific reasons cited for the F-16's relatively low cost and the F-18's relatively high cost are listed below.

### F-16

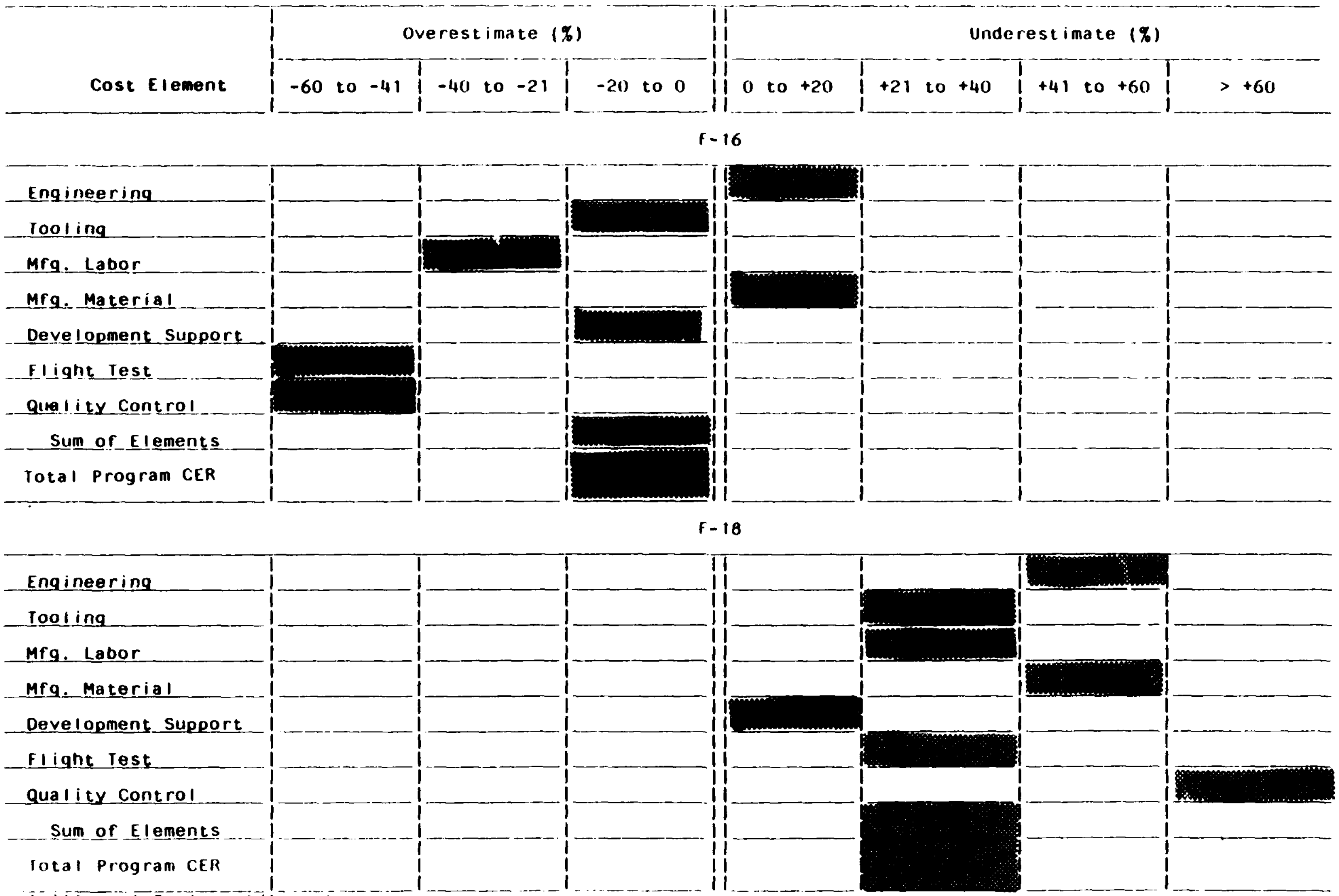
1. Emphasis on simplicity[2]
    a. Structural materials are high percentage aluminum (79 percent) and very low percentage steel, titanium, and composites (11 percent)

[1]More precise values could not be provided because of proprietary restrictions.

[2]List of examples provided by Gordon Fuqua of General Dynamics, Fort Worth Division.

Table 25

COMPARISON OF F-16 AND F-18 ESTIMATED COSTS WITH ACTUALS: RELATIVE DEVIATIONS (a)




(a)(Actual-Estimate)/Actual

b. Extensive use of standard manufacturing methods--60 percent of parts are sheet aluminum.
c. Used a fully developed engine common to the F-15.
d. Relatively few fastener types employed (50 for F-16 compared with 250 for F-111).
e. Extensive use of off-the-shelf equipment items (257 out of 373 F-16 items were off the shelf; almost all items on the B-58 and F-111 were new).

2. Adherence to "design-to-cost" philosophy: No major design changes were introduced by the Air Force or General Dynamics during FSD and early production; in fact, the first group of major changes to the F-16 did not occur until the 612th aircraft.[3]

3. Relatively high production rate achieved early in program (within two years of the first delivery, General Dynamics had delivered roughly another 175 aircraft and the Europeans another 50).[4]

## F-18

1. Extensive use of composites: Roughly 11 percent of the F-18 structure weight is composites, far higher than any prior aircraft.[5]

2. Carrier-based F-18 is actually an adaptation of land-based YF-17, an adaptation that was complicated by the fact that the original design was done by Northrop while the redesign was primarily the responsibility of McDonnell.[6]

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[3]This initial set of modifications is known as Phase 1 of the Multinational Staged Improvement Program or Engineering Change Proposal 350.

[4]See Ref. 5, p. 100.

[5]Note, however, that the AV-8B, which was also developed by McDonnell Douglas and in roughly the same timeframe as the F-18, has approximately 25 percent of its structure weight in composites.

[6]"On January 22, 1976, the U.S. Navy gave McDonnell Douglas the go-ahead to develop the carrier-based F-18. Northrop, the company that conceived the basic design of the F-18 as the F-17, became an associate contractor, assigned 40 percent of airframe development and airframe production" (see Ref. 6, p. 164).

It has also been suggested that F-18 costs could be expected to be higher than the norm because the aircraft was designed to satisfy both fighter and attack missions. However, in retrospect we do not feel that this was a major contributor to the F-18's relatively high cost, because the fighter and attack configurations turned out to be so similar (in the attack version, a FLIR and laser tracker replace fuselage-mounted Sparrow missiles).

3. Difficulty in Northrop/McDonnell relationship (at one point, the two firms were engaged in a court battle).

4. Relatively slow production rate buildup: FSD (11 aircraft) was followed by pilot production (9 aircraft) and limited production (25 aircraft) before initial full-scale production (60 aircraft).

## ASSESSING THE STABILITY OF VARIABLE COEFFICIENTS

A comparison of the existing equation set (from Table 21, Part B) with an analogous equation set that includes the F-16 and F-18 is presented in Table 26. Overall, a one-to-one pairing of variable exponents indicates that the updated equation set places a little less emphasis on weight and a little more emphasis on speed--what one might expect as a result of adding two relatively small, fast aircraft to the estimating sample. However, in general, the changes in equation coefficients are relatively minor. Furthermore, it should also be noted that based on Cook's Distance, neither the F-16 nor the F-18 is indicated to be an influential observation.

## CHOOSING BETWEEN THE EXISTING (32-AIRCRAFT) AND MODIFIED (34-AIRCRAFT) EQUATION SETS

We conclude that from a statistical standpoint, inclusion of the F-16 and F-18 in the estimating sample makes little difference. However, since most users would prefer to use an equation set that was based on the most up-to-date information, the modified equation set (Part B of Table 26) is selected as the recommended set.

*Table 26*

COMPARISON OF ALL-MISSION TYPE EQUATION SETS WITH AND WITHOUT F-16 AND F-18

| Part A: Without F-16/F-18 Equation | $R^2$ | SEE | F | N | Part B: With F-16/F-18 Equation | $R^2$ | SEE | F | N |
|---|---|---|---|---|---|---|---|---|---|
| $ENGR_{100} = .0133\ EW^{.811}\ SP^{.793}$ (.001) (.030) | .75 | .57 | 12 | 11 | $ENGR_{100} = .0103\ EW^{.777}\ SP^{.894}$ (.000) (.010) | .72 | .55 | 13 | 13 |
| $TOOL_{100} = .0221\ EW^{.778}\ SP^{.680}$ (.000) (.002) | .93 | .26 | 52 | 11 | $TOOL_{100} = .0201\ EW^{.777}\ SP^{.696}$ (.000) (.000) | .92 | .25 | 56 | 13 |
| $LABR_{100} = .165\ EW^{.820}\ SP^{.456}$ (.000) (.018) | .91 | .29 | 42 | 11 | $LABR_{100} = .141\ EW^{.820}\ SP^{.484}$ (.000) (.013) | .88 | .31 | 38 | 13 |
| $MATL_{100} = .299\ EW^{.954}\ SP^{.526}$ (.000) (.008) | .94 | .27 | 64 | 11 | $MATL_{100} = .241\ EW^{.921}\ SP^{.621}$ (.000) (.003) | .91 | .30 | 51 | 13 |
| $DS = .0323\ EW^{.660}\ SP^{1.21}$ (.026) (.033) | .54 | .90 | 5 | 11 | $DS = .0251\ EW^{.630}\ SP^{1.30}$ (.016) (.012) | .54 | .82 | 6 | 13 |
| $FT = .596\ EW^{.336}\ SP^{.858}\ TESTAC^{1.11}$ (.038) (.040) (.020) | .85 | .48 | 14 | 11 | $FT = .687\ EW^{.325}\ SP^{.822}\ TESTAC^{1.21}$ (.032) (.037) (.010) | .83 | .48 | 15 | 13 |
| $QC_{100} = .076 \times LABR_{100}$ if cargo aircraft | -- | -- | -- | 2 | $QC_{100} = .076 \times LABR_{100}$ if cargo aircraft | -- | -- | -- | 3 |
| $.126 \times LABR_{100}$ if non-cargo aircraft | -- | -- | -- | 9 | $= .133 \times LABR_{100}$ if non-cargo aircraft | -- | -- | -- | 11 |
| $PROG_{100} = 3.12\ EW^{.814}\ SP^{.676}$ (.000) (.008) | .88 | .35 | 30 | 11 | $PROG_{100} = 2.57\ EW^{.798}\ SP^{.736}$ (.000) (.003) | .85 | .36 | 29 | 13 |

NOTE: The F-16 and F-18 did not show up as influential observations in any of the regressions listed above (using Cook's Distance as the measure).

# XIV. CONCLUDING REMARKS

## RECOMMENDED EQUATION SET

The equation set that we recommend is presented in Table 27. It is based on an estimating sample of 13 post-1960 aircraft (four attack aircraft, two bombers and transports, six fighters, and one trainer). The ranges of the variables used in the derivation of the set are as follows:

| Characteristic | Data Base Range |
|---|---|
| Empty weight (lb) | 9,753 - 320,085 |
| Maximum speed (kn) | 389 - 1250+ |
| Number of flight test aircraft | 10 - 33 |

The estimating relationships in the recommended equation set vary significantly in statistical quality. Four of the CERs have standard errors of estimate of about 0.30, whereas the other three have standard errors of estimate about 0.50 or greater. None of the equations meets our standard error of estimate goal of 0.18. On the other hand, the lowest standard errors of estimate in the set are associated with cost elements (tooling, labor, and material), which typically account for 67 percent of total program cost (at a quantity of 100; at a quantity of 200, these elements account for 73 percent of total program cost). Finally, we note that there is some tendency for the engineering, development support, and total program cost equations to underestimate the costs of the most recent sample aircraft.

## CONSTRUCTION/PROGRAM VARIABLES

With respect to the incorporation of variables describing program characteristics and airframe construction characteristics, we conclude that such variables are of no help in improving the overall quality of the equation sets. Although variables characterizing the level of

Table 27

RECOMMENDED SET OF CERS (a)

| Equation | $R^2$ | SEE | F | N |
|---|---|---|---|---|
| $\frac{ENGR}{100} = .0103\ \underset{(.000)}{EW^{.777}}\ \underset{(.010)}{SP^{.894}}$ | .72 | .55 | 13 | 13 |
| $\frac{TOOL}{100} = .0201\ \underset{(.000)}{EW^{.777}}\ \underset{(.000)}{SP^{.696}}$ | .92 | .25 | 56 | 13 |
| $\frac{LABR}{100} = .141\ \underset{(.000)}{EW^{.820}}\ \underset{(.013)}{SP^{.484}}$ | .88 | .31 | 38 | 13 |
| $\frac{MATL}{100} = .241\ \underset{(.000)}{EW^{.921}}\ \underset{(.003)}{SP^{.621}}$ | .91 | .30 | 51 | 13 |
| $DS = .0251\ \underset{(.016)}{EW^{.630}}\ \underset{(.012)}{SP^{1.30}}$ | .54 | .82 | 6 | 13 |
| $FT = .687\ \underset{(.032)}{EW^{.325}}\ \underset{(.037)}{SP^{.822}}\ \underset{(.010)}{TESTAC^{1.21}}$ | .83 | .48 | 15 | 13 |
| $\frac{QC}{100} = .076 \times \frac{LABR}{100}$ if cargo aircraft | -- | -- | -- | 2 |
| $= .133 \times \frac{LABR}{100}$ if non-cargo aircraft | -- | -- | -- | 11 |
| $\frac{PROG}{100} = 2.57\ \underset{(.000)}{EW^{.798}}\ \underset{(.003)}{SP^{.736}}$ | .85 | .36 | 29 | 13 |

(a)Repeated from Table 26, Part B.

system integration were frequently found to be statistically significant, they did not, as a rule, result in any substantial improvement in the quality of the equations. In most cases, the

equations incorporating such variables did not produce results that we viewed as credible. Moreover, even in those few instances where the equations did produce credible results, the reduction in the standard error of estimate was never more than two or three percentage points.

## COMPARISON TO DAPCA III

Now that a new set of CERs has been determined for the full estimating sample, the inevitable question becomes: How does the new set differ from the prior set (DAPCA III)? In this subsection, we attempt to answer this question by comparing the current recommended set of estimating relationships (Table 27) to the DAPCA III estimating relationships (Table 28) on the basis of: (a) standard errors of estimate, and (b) predictive capability. Before proceeding, however, we make note of a number of factors that complicate this comparison.

1. **Different Samples.** The sample used to derive the current recommended set has added the F-101, F-15, F-16, F-18, S-3, and A-10 to the estimating sample. Additionally, several older fighters (the F3D, F-86, and F-89), which had been dropped from the DAPCA III estimating sample, were reintroduced.[1]
2. **Different Measures of Airframe Size.** The current recommended set uses empty weight as the size variable, whereas DAPCA III uses airframe unit weight.
3. **Different Types of Initial Coefficient Estimates.** The current recommended set provides *mean* estimates of the initial coefficient, whereas DAPCA III provides *median* estimates.[2]

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[1]They were reintroduced to bolster the size of the fighter subsample.

[2]As discussed in Sec. III, if cost is estimated in a log-linear form, then the factor for adjusting a median estimate to a mean estimate is given by $e^{SEE^2/2}$.

Table 28

DAPCA III ESTIMATING RELATIONSHIPS(a)

| Estimating Relationship | $R^2$ | SEE | F | N | Residual Pattern |
|---|---|---|---|---|---|
| $ENCR_{100} = .0234\ AUW^{.656}\ SP^{.960}$ <br> $(.000)\ (.008)$ | .90 | .26 | 26 | 9(b) | None |
| $TOOL_{100} = .472\ AUW^{.638}\ SP^{.499}$ <br> $(.000)\ (.025)$ | .71 | .41 | 27 | 25 | None |
| $LABR_{100} = .353\ AUW^{.793}\ SP^{.423}$ <br> $(.000)\ (.021)$ | .85 | .34 | 62 | 25 | None |
| $MATL_{100} = .0763\ AUW^{.880}\ SP^{.867}$ <br> $(.000)\ (.000)$ | .86 | .36 | 67 | 25 | CUR:UNDER |
| $DS = (.000626\ AUW^{.688}\ SP^{1.21})$(c) <br> $(.000)\ (.003)$ | .53 | .72 | 12 | 24 | CUR:OVER |
| $+ (.0000354\ AUW^{.724}\ SP^{1.92})$(d) <br> $(.000)\ (.000)$ | .68 | .66 | 23 | 24 | None |
| $FT = .192\ AUW^{.710}\ SP^{.586}\ TESTAC^{.716}\ CARGODV^{-1.56}$ <br> $(.000)\ (.084)(.001)\ (.011)$ | .81 | .44 | 21 | 25 | None |
| $QC_{100} = .085 * LABR_{100}$ if cargo aircraft | -- | -- | -- | -- | -- |
| $= .12 * LABR_{100}$ otherwise if non-cargo aircraft | | | | | |
| $PROG_{100} = 6.22\ AUW^{.728}\ SP^{.737}$ <br> $(.000)\ (.000)$ | .88 | .27 | 79 | 24 | None |

(a)Taken from Ref. 3; all cost elements estimated directly in dollars have been converted to 1977 levels by adjusting the initial coefficient.
(b)Post-1957 aircraft excluding A-7, KC-135, T-39.
(c)Labor component of development support.
(d)Material component of development support.

### Standard Errors of Estimate

As shown in Table 29, the results with respect to the comparison of standard errors of estimate are mixed. When compared to DAPCA III, the current set has lower standard errors of estimate for the tooling, labor, and material elements (which account for 66 percent of total cost at a quantity of 100) and higher standard errors of estimate for the engineering, development support, and flight test cost elements (which account for 30 percent of total cost at a quantity of 100).

### Relative Accuracy

A comparison of how well the current equation set and the DAPCA III equation set estimate the 13 post-1960 aircraft is provided in Table 30. Judging by the overall average of the absolute relative deviations, there is little difference. However, the current equation set underestimates fewer aircraft than does DAPCA III.

Table 29

COMPARISON OF STANDARD ERRORS OF ESTIMATE

| Cost Element | Percent of Total Cost at Q = 100 | Standard Error of Estimates (log) | |
|---|---|---|---|
| | | DAPCA III | Current |
| Engineering | 19 | .26 | .55 |
| Tooling | 16 | .41 | .25 |
| Manufacturing labor | 34 | .34 | .31 |
| Manufacturing material | 16 | .36 | .30 |
| Development support | 5 | .72(b)<br>.66(c) | .82 |
| Flight test | 6 | .44 | .48 |
| | 96(a) | | |

(a)Quality control is other 4%.
(b)Labor component of development support.
(c)Material component of development support.

Table 30

PERCENT BY WHICH ACTUAL COST EXCEEDS (+) OR FALLS SHORT (-)
OF ESTIMATED COST, USING ESTIMATES OBTAINED
WITH DAPCA III AND CURRENT EQUATION SETS

| | Sum of Elements | | Total Program CER | |
|---|---|---|---|---|
| Aircraft | DAPCA III | Current | DAPCA III | Current |
| A-6 | +11 | 0 | +10 | 0 |
| A-7 | -81 | -86 | -86 | -85 |
| A-10 | +15 | +13 | +17 | +15 |
| C-5 | +12 | + 4 | +14 | + 5 |
| C-141 | -43 | -64 | -46 | -67 |
| F-4 | + 7 | -14 | + 2 | -16 |
| F-111 | +17 | + 2 | +16 | + 7 |
| F-14 | - 7 | -22 | -11 | -20 |
| F-15 | + 9 | -15 | + 6 | - 5 |
| F-16 | - 8 | -23 | -13 | -20 |
| F-18 | +36 | +33 | +34 | +36 |
| T-39 | -36 | -37 | -40 | -39 |
| S-3 | +44 | +39 | +45 | +40 |
| Average of absolute values | 25 | 27 | 26 | 27 |
| Number underestimated (+) | 8 | 5 | 8 | 5 |
| Number overestimated (-) | 5 | 7 | 5 | 7 |

## Level of Estimates

An indication of how much the estimates produced by the current equation set exceed (or fall short) of those produced by DAPCA III is provided in Table 31. As there are only two negative numbers in the table, and both of those are small, it is reasonable to suggest that the current equation set will produce estimates that are greater than or equal to those produced by DAPCA III.

## COST-QUANTITY SLOPES

Minimum, maximum, and average cost-quantity slopes for the full estimating sample are provided in Table 33. A comparison of slopes by mission type is provided in Table 32. With two exceptions (the attack aircraft material slope and the fighter quality control slope), the

Table 31

COMPARISON OF RELATIVE LEVELS OF ESTIMATES OBTAINED USING DAPCA III AND CURRENT EQUATION SETS

| | Characteristics | | | Percent by Which Current Set Estimate Exceeds (+) or Falls Short (-) of DAPCA III Estimate | |
|---|---|---|---|---|---|
| Aircraft | Airframe Unit Weight (lb) | Empty Weight (lb) | Speed (kn) | Sum of Elements | Total Program CER |
| A-6 | 17,150 | 25,298 | 561 | +13 | +11 |
| A-7 | 11,621 | 15,497 | 595 | + 2 | 0 |
| A-10 | 14,842 | 19,856 | 389 | + 2 | + 1 |
| C-5 | 279,145 | 320,085 | 495 | + 9 | +10 |
| C-141 | 104,322 | 136,900 | 491 | +15 | +15 |
| F-4 | 17,220 | 27,530 | 1222 | +23 | +18 |
| F-111 | 33,150 | 46,170 | 1262 | +17 | +11 |
| F-14 | 26,500 | 36,825 | * | +14 | + 4 |
| F-15 | 17,550 | 26,795 | * | +26 | +14 |
| F-16 | 9,565 | 14,062 | * | +14 | + 6 |
| F-18 | 16,300 | 20,583 | * | + 5 | - 3 |
| T-39 | 7,027 | 9,753 | 468 | + 1 | - 1 |
| S-3 | 18,536 | 26,581 | 429 | +10 | + 9 |

*1000+ (actual value classified).

Table 32

CUMULATIVE TOTAL COST-QUANTITY SLOPES

| | Engineering Hours | Tooling Hours | Mfg. Labor Hours | Mfg. Material Cost | Quality Control Hours | Total Program Cost |
|---|---|---|---|---|---|---|
| Number of observations | 34 | 34 | 34 | 34 | 22 | 34 |
| Range (%) | 106-132 | 108-158 | 140-182 | 140-200 | 126-234 | 124-144 |
| Average (%) | 114 | 122 | 154 | 172 | 158 | 134 |
| Exponent | .189 | .287 | .623 | .782 | 660 | .422 |

NOTES: Results are based on first 200 units; cumulative average slope = cumulative total slope divided by two.

Table 33

CUMULATIVE TOTAL COST-QUANTITY SLOPES (%) BY MISSION TYPE

| Sample | Engineering Hours | Tooling Hours | Mfg. Labor Hours | Mfg. Material Cost | Quality Control Hours | Total Program Cost |
|---|---|---|---|---|---|---|
| Total | 114 | 122 | 154 | 172 | 158 | 134 |
| Attack | 110 | 122 | 154 | 180 | 154 | 134 |
| Bomber/transport | 116 | 116 | 154 | 170 | 152 | 136 |
| Fighter | 116 | 124 | 156 | 172 | 170 | 132 |

slopes show little deviation about the full sample averages. However, even changes in slope as small as 1 percentage point can have a major effect on cost. The extent of this effect will of course vary with the quantity and the slope magnitude, but for a run of 700 aircraft, a 1 percentage point increase in the slope will usually increase total costs by at least 10 percent.

Since the estimating relationships in the recommended equation set (Table 27) are based on a sample limited to post-1960 aircraft, average cumulative total slopes for the post-1960 sample are also determined and then compared to the full sample:

| Cost Element | Full Sample | Post-1960 Sample | |
|---|---|---|---|
| | | Slope | Exponent |
| Engineering | 114% | 112% | .163 |
| Tooling | 122 | 120 | .263 |
| Manufacturing labor | 154 | 156 | .641 |
| Manufacturing material | 172 | 174 | .799 |
| Quality control | 158 | 156 | .641 |
| Total program cost | 134 | 132 | .401 |

As indicated, the differences are slight and hardly a basis for drawing any conclusions. However, in the interest of consistency, the slopes based on the post-1960 sample are suggested for use with the recommended equation set.

## FULLY BURDENED LABOR RATES

All cost elements estimated directly in dollars are in 1977 dollars. Suggested 1977 fully burdened, hourly labor rates (and those used to estimate total program cost) are:

| | |
|---|---|
| Engineering | 27.50 |
| Tooling | 25.50 |
| Manufacturing labor | 23.50 |
| Quality control | 24.00 |

For estimates in 1986 dollars, the following hourly labor rates and adjustment factors are suggested:

| | |
|---|---|
| Engineering | 59.10 |
| Tooling | 60.70 |
| Manufacturing labor | 50.10 |
| Quality control | 55.40 |
| Manufacturing material (index) | 1.94 |
| Development support (index) | 1.94 |
| Flight test (index) | 1.94 |
| Total program (index) | 2.13 |

The 1986 labor rates are based on data provided by seven contractors:

| Labor Category | Hourly Rates ($) Average | Range | Range About Average (%) |
| --- | --- | --- | --- |
| Engineering | 59.10 | 47.70-70.00 | -19, +18 |
| Tooling | 60.70 | 56.50-65.00 | - 7, + 7 |
| Manufacturing labor | 50.10 | 41.70-58.00 | -17, +16 |
| Quality control | 55.40 | 49.10-62.60 | -11, +13 |

Note that with the exception of tooling, the range about the average rate is at least + or -10 percent. Such differences could arise from differences in accounting practices, business bases, and capital investment. Irrespective of cause, however, labor rate variation is one more component of a larger uncertaintv that already includes the error associated with statistically derived estimating relationships and questions about the proper cost-quantity slope. Furthermore, in addition to the inter-contractor differences, these rates are also subject to temporal change--accounting procedures, relative capital/labor ratio, etc. Thus, the 1986 fully burdened rate is qualitatively different than the 1977 rate. Unfortunately, trying to estimate the magnitude of such quality changes, even very crudely, is a study in itself and beyond the scope of this analysis.

The material, development support, and flight test escalation indexes are based on data provided in AFR 173-13.[3] For the years 1977-1984, the airframe index presented in Table 5-3 ("Historical Aircraft Component Inflation Indices") was used. For the years 1985 and 1986, the aircraft and missile procurement index presented in Table 5-2 ("USAF Weighted Inflation Indices Based on OSD Raw Inflation and Outlay Rates") was used. The total program cost adjustment factor was then determined on the basis of a weighted average (at $q = 100$) of the individual cost elements.

[3] See Ref. 7.

# Appendix A

## USE OF MISSION DUMMY VARIABLES

As stated in the Introduction, one of the purposes of this study is to examine the utility of dividing the estimating sample into subsample representing the major mission types (attack aircraft, fighters and bomber/transport aircraft). This is to be done by analyzing each subsample separately. However, an alternative approach to this issue would assign yes/no-type dummy variables for each mission type and use the full sample. Thus, each dummy mission variable would take on a value of one for aircraft in its class and zero for other aircraft. Additionally, each could be applied to either the equation intercept or to the equation slope. The effect of each application is illustrated in Fig. A.1.

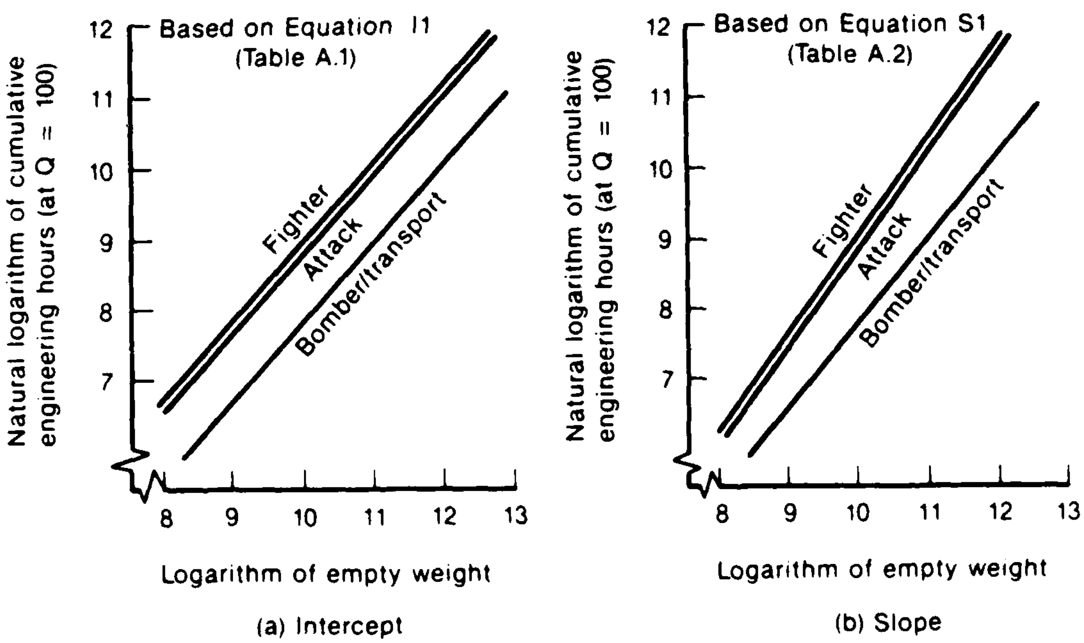


Fig. A.1—Effect of mission dummy variables on slope and intercept

Since this was a supplemental effort, the analysis was limited to the following three equation forms:

| Application | Explanatory Variables |
|---|---|
| Intercept | Empty weight |
| Slope | Empty weight |
| Intercept | Empty weight and speed |

Intuitively, it was felt that for a given weight, fighters would be the most costly mission type, followed by attack aircraft, and then bombers and transports. Thus, bombers and transports were assumed to be the baseline and consequently only two mission dummy variables were required for the regression analysis--the fighter designator (F) and the attack aircraft designator (A). Furthermore, the variable significance level was dropped to 10 percent. Thus, if a mission dummy variable was not significant at the 10 percent level, it was deleted from the analysis and the estimating relationship redetermined. Consequently, in some instances, the estimating relationship collapsed into a form without any mission designators.

The estimating relationships meeting our initial screening criterion relative to variable significance are summarized in Tables A.1, A.2, and A.3. Overall, the results were disappointing--the equations had difficulties associated with residual patterns, exponent magnitude, and counterintuitive reversals of our a priori rank ordering of mission-type costs. Consequently, the use of mission dummy variables to stratify the full estimating sample was not pursued beyond that which is documented in this appendix.

Table A.1

MISSION DUMMY VARIABLES: INTERCEPT/EMPTY WEIGHT

| Eq. No. | Equation | Statistics $R^2$ | SEE | F | N | Relative Deviations (%) A-10 | C-141 | F-14 | F-15 | Abs Avg | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 11 | $ENGR_{100} = .0191e^{\underset{(.015)}{1.07A} + \underset{(.010)}{1.09F}}\ \underset{(.000)}{EW^{1.17}}$ | .58 | .59 | 12 | 30 | +7 | -45 | +35 | +48 | 34 | RP:CUR:UNDER<br>IO:B-58 |
| 12 | $TOOL_{100} = 7.12e^{\underset{(.077)}{-.280A}}\ \underset{(.000)}{EW^{.675}}$ | .69 | .43 | 31 | 30 | -50 | -95 | +4 | +7 | 39 | BT > A |
| 13 | $LABR_{100} = 2.54e^{\underset{(.095)}{.179F}}\ \underset{(.000)}{EW^{.838}}$ | .83 | .32 | 65 | 30 | -12 | -70 | +7 | +15 | 26 | |
| 14 | $MATL_{100} = .185e^{\underset{(.014)}{.834A} + \underset{(.014)}{.785F}}\ \underset{(.000)}{EW^{1.26}}$ | .78 | .45 | 30 | 30 | -8 | -36 | +18 | +26 | 22 | EXP MAG:EW<br>A > F<br>RP:CUR:UNDER<br>IO:B-58 |
| 15 | $DS = .0647e^{\underset{(.069)}{1.09A} + \underset{(.019)}{1.47F}}\ \underset{(.001)}{EW^{1.24}}$ | .38 | .91 | 5 | 30 | +3 | -227 | +4 | +45 | 70 | RP:CUR:UNDER |
| 16 | $FT = 2859e^{\underset{(.062)}{-.563F}}\ \underset{(.000)}{TESTAC^{1.43}}$ | .36 | .85 | 7 | 30 | -94 | +30 | +57 | +18 | 50 | EXP MAG:TESTAC<br>BT, A > F<br>RP:CUR:UNDER<br>IO:F-4 |
| 17 | $QC_{100} = 1.08e^{\underset{(.095)}{.372F}}\ \underset{(.000)}{EW^{.712}}$ | .57 | .51 | 10 | 18 | +2 | -205 | -11 | +33 | 63 | RP:CUR:UNDER<br>IO:A-7, C-141 |
| 18 | $PROG_{100} = 22.9e^{\underset{(.066)}{.483A} + \underset{(.023)}{.614F}}\ \underset{(.000)}{EW^{1.00}}$ | .76 | .39 | 27 | 30 | -14 | -72 | +15 | +30 | 33 | EXP MAG:EW<br>RP:CUR:UNDER<br>IO:B-58 |

Table A.2

MISSION DUMMY VARIABLES: SLOPE/EMPTY WEIGHT

| Eq. No. | Equation | $R^2$ | SEE | F | N | A-10 | C-141 | F-14 | F-15 | Abs Avg | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Statistics | | | | Relative Deviations (%) | | | | | |
| S1 | $ENGR_{100} = .0269\ EW^{1.14 + .103A + .107F}$ <br> (.000) (.012) (.006) | .59 | .58 | 13 | 30 | +9 | -41 | +32 | +47 | 32 | RP:CUR:UNDER <br> IO:A-3,B-58 |
| S2 | $TOOL_{100} = 7.01\ EW^{.676 - .0283A}$ <br> (.000)(.074) | .69 | .43 | 31 | 30 | -50 | -95 | +4 | +7 | 39 | BT > A |
| S3 | $LABR_{100} = .664\ EW^{.948 + .0316A + .0428F}$ <br> (.000) (.089) (.028) | .84 | .31 | 46 | 30 | -18 | -63 | -1 | +12 | 24 | |
| S4 | $MATL_{100} = .261\ EW^{1.23 + .0786A + .0751F}$ <br> (.000) (.013) (.011) | .78 | .45 | 31 | 30 | -6 | -34 | +15 | +25 | 20 | EXP MAG:EW <br> A > F <br> RP:CUR:UNDER <br> IO:B-58 |
| S5 | $DS = .0841\ EW^{1.22 + .107A + .148F}$ <br> (.000) (.058) (.012) | .40 | .89 | 6 | 30 | +6 | -212 | -3 | +43 | 66 | RP:CUR:UNDER <br> IO:A-3 |
| S6 | $FT = 3040\ TESTAC^{1.39 - .0488F}$ <br> (.000) (.093) | .34 | .86 | 7 | 30 | -92 | +29 | +56 | +17 | 48 | EXP MAG:TESTAC <br> BT,A > F <br> RP:CUR:UNDER <br> IO:F-4 |
| S7 | $QC_{100} = 1.06\ EW^{.713 + .0378F}$ <br> (.000) (.085) | .58 | .51 | 10 | 18 | +3 | -203 | -13 | +33 | 63 | RP:CUR:UNDER <br> IO:A-7,C-141 |
| S8 | $PROG_{100} = 24.3\ EW^{.995 + .0486A + .0626F}$ <br> (.000) (.050) (.013) | .77 | .39 | 28 | 30 | -13 | -70 | +12 | +29 | 31 | EXP MAG:EW <br> RP:CUR:UNDER <br> IO:B-58 |

Table A.3

MISSION DUMMY VARIABLES: INTERCEPT/EMPTY WEIGHT AND SPEED

| Eq. No. | Equation | $R^2$ | SEE | F | N | A-10 | C-141 | F-14 | F-15 | Abs Avg | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Statistics | | | | Relative Deviations (%) | | | | | |
| C1 | $ENGR_{100} = .000457e^{.457A} EW^{.894} SP^{1.10}$ <br> (.023) (.000) (.000) | .74 | .46 | 25 | 30 | +42 | -28 | +19 | +29 | 30 | A > F <br> RP:CUR:UNDER <br> IO:S-3 |
| C2 | $TOOL_{100} = .403e^{-.618A - .651F} EW^{.526} SP^{.735}$ <br> (.018) (.018) (.000) (.000) | .81 | .35 | 27 | 30 | -11 | -80 | -16 | -18 | 31 | BT > A > F |
| C3 | $LABR_{100} = .281\ EW^{.829} SP^{.364}$ <br> (.000) (.004) | .86 | .29 | 83 | 30 | +1 | -62 | -7 | +2 | 18 | |
| C4 | $MATL_{100} = .0385e^{.442A} EW^{1.08} SP^{.934}$ <br> (.002) (.000) (.000) | .90 | .31 | 77 | 30 | +28 | - 21 | -5 | 0 | 13 | EXP MAG:EW <br> A > F <br> RP:CUR:UNDER |
| C5 | $DS = .00683\ EW^{.801} SP^{1.19}$ <br> (.000) (.001) | .47 | .82 | 12 | 30 | +48 | -195 | -14 | +24 | 70 | RP:CUR:UNDER <br> IO:F-104 |
| C6 | $FT = .00238^{-.613F} TESTAC^{.906} EW^{.504} SP^{1.51}$ <br> (.021) (.001) (.001) (.000) | .74 | .56 | 18 | 30 | +34 | -16 | +3 | -22 | 19 | BT,A > F |
| C7 | $QC_{100} = .0116\ EW^{.715} SP^{.697}$ <br> (.000) (.008) | .68 | .45 | 16 | 18 | +31 | -155 | -27 | +23 | 59 | RP:CUR:UNDER <br> IO:A-10,C-5, <br> C-141,S-3 |
| C8 | $PROG_{100} = .994e^{.181A} EW^{.869} SP^{.744}$ <br> (.097)(.000) (.000) | .87 | .29 | 58 | 30 | +17 | -58 | -4 | +11 | 22 | A > F <br> RP:CUR:UNDER |

# Appendix B

## CORRELATION MATRIXES

This appendix contains correlation matrixes for the full estimating sample (32 aircrft).[1] Table B.1 provides Pearson correlation coefficients for all possible pairwise combinations of dependent and independent variables. Table B.2 provides coefficients for all possible pairwise combinations of independent variables.

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[1]These correlation coefficients were used in conjunction with the work completed before the incorporation of the F-16 and F-18.

Table B.1

CORRELATION MATRIX: COST VARIABLES WITH POTENTIAL EXPLANATORY VARIABLES

| EXPLANATORY VARIABLES | COST VARIABLES | | | | | | |
|---|---|---|---|---|---|---|---|
| | ln ENGR | ln TOOL | ln LABR | ln MATL | ln DEVSPT | ln FLTTST | ln PROG |
| SIZE | | | | | | | |
| ln AUW | 0.69 | 0.79 | 0.90 | 0.84 | 0.53 | 0.35 | 0.84 |
| ln EW | 0.70 | 0.83 | 0.92 | 0.86 | 0.56 | 0.41 | 0.86 |
| ln WTAREA | 0.60 | 0.77 | 0.85 | 0.79 | 0.42 | 0.22 | 0.77 |
| PERFORMANCE | | | | | | | |
| ln SP | 0.32 | 0.15 | 0.02 | 0.17 | 0.34 | 0.60 | 0.20 |
| ln SPCLS | 0.40 | 0.19 | 0.05 | 0.22 | 0.39 | 0.61 | 0.24 |
| ln CLIMB | 0.20 | -0.03 | -0.14 | -0.03 | 0.20 | 0.45 | 0.02 |
| ln USELD | 0.37 | 0.40 | 0.44 | 0.44 | 0.24 | 0.20 | 0.41 |
| CONSTRUCTION | | | | | | | |
| ln ULTLD | -0.39 | -0.61 | -0.62 | -0.57 | -0.23 | -0.11 | -0.56 |
| ln CARRDV | -0.14 | -0.27 | -0.14 | -0.17 | -0.19 | -0.06 | -0.19 |
| ln ENGLOC | 0.25 | 0.45 | 0.49 | 0.44 | 0.11 | -0.04 | 0.41 |
| ln WGTYPE | 0.30 | 0.32 | 0.12 | 0.27 | 0.43 | 0.62 | 0.29 |
| ln WGWET | -0.15 | -0.07 | -0.17 | -0.12 | -0.02 | 0.13 | -0.14 |
| ln EWAUW | -0.30 | -0.15 | -0.33 | -0.31 | -0.05 | 0.25 | -0.26 |
| ln AVAUW | -0.21 | -0.21 | -0.29 | -0.31 | 0.08 | 0.18 | -0.22 |
| ln BLBOX | 0.77 | 0.58 | 0.67 | 0.76 | 0.61 | 0.45 | 0.72 |
| PROGRAM | | | | | | | |
| ln TESTAC | 0.22 | 0.29 | 0.06 | 0.10 | 0.45 | 0.59 | 0.22 |
| ln TOOLCP | -0.50 | -0.42 | -0.61 | -0.58 | -0.32 | -0.15 | -0.55 |
| ln ENGDV | 0.24 | 0.24 | 0.28 | 0.18 | 0.14 | 0.12 | 0.26 |
| ln EXPDV | 0.11 | -0.06 | -0.05 | -0.01 | 0.03 | -0.05 | 0.00 |
| ln PRGDV | -0.60 | -0.41 | -0.48 | -0.51 | -0.69 | -0.55 | -0.56 |

Table B.2

CORRELATION MATRIX FOR IDENTIFICATION OF PAIRWISE COLLINEARITY

| EXPLANATORY VARIABLE | SIZE | | | TECHNICAL/PERFORMANCE | | | | CONSTRUCTION | | | | | | | | PROGRAM | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ln AUW | ln EW | ln WTAREA | ln SP | ln SPCLS | ln CLIMB | ln USELD | ln ULTLD | ln CARRDV | ln ENGLOC | ln WGTYPE | ln WGWET | ln EWAUW | ln AVAUW | ln BLBOX | ln TESTAC | ln TOOLCP | ln ENGDV | ln EXPDV | ln PRGDV |
| SIZE | | | | | | | | | | | | | | | | | | | | |
| ln AUW | 1.00 | | | | | | | | | | | | | | | | | | | |
| ln EW | 0.99 | 1.00 | | | | | | | | | | | | | | | | | | |
| ln WTAREA | 0.90 | 0.90 | 1.00 | | | | | | | | | | | | | | | | | |
| TECHNICAL/PERFORMANCE | | | | | | | | | | | | | | | | | | | | |
| ln SP | -0.22 | -0.19 | -0.30 | 1.00 | | | | | | | | | | | | | | | | |
| ln SPCLS | -0.16 | -0.15 | -0.29 | 0.92 | 1.00 | | | | | | | | | | | | | | | |
| ln CLIMB | -0.36 | -0.34 | -0.48 | 0.89 | 0.86 | 1.00 | | | | | | | | | | | | | | |
| ln USELD | 0.50 | 0.51 | 0.51 | -0.20 | -0.21 | -0.30 | 1.00 | | | | | | | | | | | | | |
| CONSTRUCTION | | | | | | | | | | | | | | | | | | | | |
| ln ULTLD | -0.76 | -0.77 | -0.84 | 0.53 | 0.44 | 0.63 | -0.56 | 1.00 | | | | | | | | | | | | |
| ln CARRDV | -0.27 | -0.26 | -0.37 | 0.03 | -0.14 | 0.01 | 0.03 | 0.28 | 1.00 | | | | | | | | | | | |
| ln ENGLOC | 0.63 | 0.62 | 0.78 | -0.59 | -0.48 | -0.70 | 0.52 | -0.89 | -0.29 | 1.00 | | | | | | | | | | |
| ln WGTYPE | -0.07 | -0.03 | -0.18 | 0.66 | 0.51 | 0.50 | -0.10 | 0.87 | 0.10 | -0.27 | 1.00 | | | | | | | | | |
| ln WGWET | -0.26 | -0.21 | -0.20 | 0.02 | -0.04 | 0.12 | -0.39 | 0.13 | 0.14 | -0.22 | 0.26 | 1.00 | | | | | | | | |
| ln EWAUW | -0.56 | -0.46 | -0.57 | 0.36 | 0.21 | 0.36 | -0.19 | 0.32 | 0.28 | -0.37 | 0.38 | 0.47 | 1.00 | | | | | | | |
| ln AVAUW | -0.65 | -0.52 | -0.65 | 0.34 | 0.20 | 0.28 | -0.35 | 0.45 | 0.46 | -0.43 | 0.41 | 0.35 | 0.60 | 1.00 | | | | | | |
| ln BLBOX | 0.68 | 0.67 | 0.63 | -0.04 | 0.01 | -0.19 | 0.57 | -0.55 | 0.01 | 0.49 | 0.09 | -0.17 | -0.32 | -0.07 | 1.00 | | | | | |
| PROGRAM | | | | | | | | | | | | | | | | | | | | |
| ln TESTAC | -0.13 | -0.09 | -0.25 | 0.54 | 0.59 | 0.52 | -0.21 | 0.19 | -0.26 | -0.38 | 0.42 | 0.28 | 0.35 | 0.29 | -0.13 | 1.00 | | | | |
| ln TOOLCP | -0.63 | -0.61 | -0.68 | 0.24 | 0.18 | 0.35 | -0.43 | 0.51 | -0.06 | -0.61 | 0.10 | 0.30 | 0.63 | 0.24 | -0.61 | 0.30 | 1.00 | | | |
| ln ENGDV | 0.21 | 0.20 | 0.16 | -0.09 | -0.11 | -0.17 | 0.28 | -0.20 | -0.20 | 0.26 | 0.06 | 0.04 | -0.15 | -0.01 | 0.23 | 0.19 | -0.40 | 1.00 | | |
| ln EXPDV | -0.09 | -0.11 | -0.05 | -0.14 | -0.01 | -0.19 | -0.13 | -0.12 | 0.12 | 0.07 | -0.20 | 0.07 | -0.01 | 0.28 | 0.13 | 0.00 | 0.04 | -0.13 | 1.00 | |
| ln PREDV | -0.34 | -0.34 | -0.17 | -0.39 | -0.44 | -0.28 | -0.18 | -0.02 | -0.02 | 0.05 | -0.38 | 0.15 | 0.18 | -0.10 | -0.61 | -0.24 | 0.36 | -0.06 | 0.85 | 1.00 |

*Note*: Combinations above and to the right of heavy line were not considered because of the study assumption that an estimating relationship would not contain more than one variable from each class.

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